QoS-Aware Mode Selection and Resource Allocation Scheme for Device-to-Device (D2D) Communication in cellular networks

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***Abstract*—In the cellular network, Device-to-Device (D2D) communication is considered to be a promising resource reuse strategy, which can enable local service opportunities and reduce system load for short-range communication. In order to suppress the interference from D2D users, the scheduler should allocate resources and select communication mode appropriately. In this paper, we analyze the constraints and system equations of D2D links in scenarios with multiclass services, and propose a joint mode selection and resource allocation (JMSRA) scheme, in which interference suppression and Quality of Service (QoS) requirements are considered. The proposed scheme optimizes communication mode for each device and allocates resource according to service demands and current state of the network. Numerical results show that the proposed JMSRA scheme achieves higher system capacity than both Pure Cellular and Force D2D schemes, especially when the maximum distance between D2D pairs or system load increases. Simulation also proves that our scheme can obtain higher service satisfaction degree in the hybrid network.**

***Index Terms*—Device-to-Device Communication, Mode Selection, Resource Allocation, QoS-aware Scheduling, Multiclass Services Scenario.**

I. Introduction

Recently, major effort has been spent on the development of next-generation wireless communication systems such as 3GPP Long Term Evolution (LTE) and WiMAX, which can provide higher data rates and multiclass services. In order to improve the performance of the cellular network, much research has been done to reuse the spectrum, such as Cognitive Radio Technology and D2D communication.

In traditional cellular networks, data is transmitted via base station (BS) or other network element. The design will limit the transmission rate when communicating devices are relatively close to each other. In this case, a direct link will be a promising add-on component to the current cellular network, which can increase system capacity by sharing resources with cellular links [1] . However, enabling Device-to-Device (D2D) communication brings a challenge in radio resource management, especially when D2D local users reuse the spectrum of cellular users. The co-channel interference may lead to high bit error rate in hybrid networks. Recently, some interference management schemes have been proposed to guarantee the communication quality of hybrid network. Studies in [2] and [3] propose several resource allocation schemes based on local awareness of the interference between cellular and D2D terminals, which then exploits the multi-user diversity to minimize the co-channel interference. In addition, power control mechanisms are investigated in [4] and [5], mainly by restrict D2D transmit power to ensure cellular link quality. However, the aforementioned studies are done under the assumption that the direct communication mode is decided only by path loss without consideration of inter-user interference and QoS requirements. In fact, when a direct link can not be supported in D2D channel, users must choose the cellular mode to ensure communication reliability.

Mode selection is important to establish a reliable and efficient communication link. Schemes are proposed in [6, 7] to optimize communication mode for D2D users. However, those studies do not cover multiclass service requirements and assume that one D2D user can only share resource with one cellular user. Such assumptions will limit scheduling flexibility and cannot meet throughput demands of high-rate services.

In this paper, we focus on a mode selection scheme considering both interference and QoS requirements of different users. A joint mode selection and resource allocation (JMSRA) scheme is proposed, which gives cellular user and D2D user the same priority in scheduling and allocates resource according to service demands. Our scheme provides three D2D modes, i.e., underlay D2D mode, dedicated D2D mode and cellular mode, and allows D2D users to share any continuous resources of cellular users or transmit on dedicated resources. Unlike the previous studies, we estimate the transmission mode by channel states in the initialization phase, but dynamically adjust the transmission mode according to the service history. In this way, the scheduling scheme will result in higher spectrum efficiency and QoS satisfaction degree.

The remainder of this paper is organized as follows. In Section II, we present the hybrid system and service model. In Section III, we discuss the scheduling problem with QoS constraints. Further, we propose a joint mode selection and resource allocation scheme in Section IV. In Section V, we analyze the performance of the proposed scheme in multiclass-service scenario. Finally, we draw a conclusion in Section VI.

The work in this paper is sponsored by 111 Project of China under Grant No. B08004.

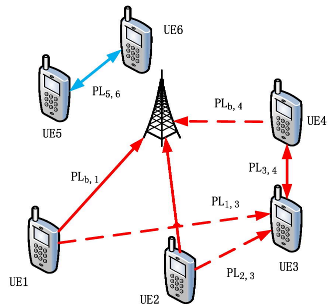

Fig. 1. The communication modes and interference scenario between devices.

II. SYSTEM MODEL

We consider a multicell deployment in LTE uplink system, where cellular users are uniformly distributed. As can be seen in Fig. 1, devices can communicate directly as a D2D link or via BS as a cellular link, e.g., UE 1 and 2 are both in cellular mode and UE 3,4 and 5,6 communicate with a direct link. In the uplink system, a cellular link suffers from the interference at BS which comes both from cellular users in adjacent cells and D2D users who share the same resources, while a D2D link suffers from the interference at the device which caused by cellular user and other D2D users on the same resource block (RB). Fig 1 also depicts the interference between devices. Since cellular user 1,2 and D2D user 5,6 are both in dedicated mode and their resources are orthogonal, no interference exists between them. However, if D2D user 3 chooses underlay mode and share the same resources with user 1, its transmit power will be an interference to the cellular link. At the same time, D2D user 3 will suffer great interference from cellular user 1 if the isolation between them is not enough.

Considering different services in the hybrid network, we focus on the characteristics of VoIP, HTTP and FTP services. VoIP service is a representation of low-speed services with high real-time requirement, and HTTP service is one of data services which demand a Guarantee Bit Rate (GBR), while FTP is a best-effort service with a high Maximum Bit Rate (MBR) target and low requirement in delay.

In this paper, we assume that D2D users could reuse uplink spectrum or communicate in dedicated mode, and BS has knowledge of current channel state and QoS requirements of all users. This can be done by decoding Sounding Reference Signal and analyzing QoS Class Identifier of bearer. With proper power control, BS can make the best decision on mode selection and resource allocation to optimize system capacity and meet users' service requirements.

III. SYSTEM EQUATIONS

A. Optimization Formulation

In this section, we study the interference and SINR calculations of dedicated and underlay users. Let's assume that we have altogether N users in the system, and some of them have a probability for a direct link. Furthermore, we define the following symbols for the hybrid system.

L	Number of Resource Blocks in the System
i, j	User device index with values $1 \leq i, j \leq N$
k, a, b	RB index with values $1 \leq k, a, b \leq L$
$PL_{b,ik}$	Total path Loss between device i and base station on RB k (including fast fading)
$PL_{u,ijk}$	Total path Loss between user i, j on RB k
$\beta_{c,ik}$	SINR for user i with cellular link on RB k
$\beta_{d,ik}$	SINR for user i with direct link on RB k
p_{ik}	Transmitting power of device i on RB k
m_i	Link mode of user i ($m_i = 1$ for D2D link and $m_i = 0$ for cellular link)
n_b	Noise power at the receiver of base station
n_u	Noise power at the receiver of user device
IoT	Interference from adjacent cells
$R_{t,i}$	Target Rate for user i
$\varepsilon_{t,i}$	Threshold of Packet Error Ratio for user i

According to Fig. 1, when user 1 chooses the cellular mode, its SINR can be expressed by:

$$\beta_{c,ik} = \frac{p_{ik}/PL_{b,ik}}{\sum\limits_{j=1,j\neq i}^{N} p_{jk}/PL_{b,jk} + IoT_b + n_b} \tag{1}$$

Similarly, SINR of user 3 with underlay D2D mode is given as follows ($PL_{u,iik}$ means the inner path loss of direct link):

$$\beta_{d,ik} = \frac{p_{ik}/PL_{u,iik}}{\sum\limits_{j=1,j\neq i}^{N} p_{jk}/PL_{u,ijk} + IoT_d + n_u} \tag{2}$$

To give a general expression, m_i is introduced to denote the communication mode of user i, then the SINR of user i is:

$$\beta_{ik} = (1 - m_i) \cdot \beta_{c,ik} + m_i \cdot \beta_{d,ik} \tag{3}$$

Since β_{ik} reflects current channel state and decides Modulation and Coding Scheme (MCS), it will affect the transmit rate directly. We define a function as $F(\beta_{ik}, \varepsilon) = r_{ik}$ to express the mapping from β_{ik} to transmit rate r_{ik}. Here ε denotes the bit error ratio (BER) which is limited by QoS requirement.

Since the Single Carrier FDMA (SC-FDMA) has been defined for the LTE uplink, designers must devise scheduling algorithms with contiguous RB allocation constraint. Using these equations and constraints, we can find the optimal mode selection vector $\mathbf{m} = \{m_1, m_2, \ldots, m_N\}$ and resource allocation matrix $\mathbf{P} = \{p_{ik}, 1 \leq i \leq N \text{ and } 0 \leq k \leq L\}$, in which p_{ik} denotes the transmitting power of user i on RB k.

$$arg\ max \sum_{i=1}^{N} \sum_{k=1}^{L} r_{ik} \tag{4}$$

subject to

$$F(\beta_{ik}, \varepsilon_{i,k}) = r_{ik} \tag{5}$$

$$\varepsilon_{i,k} \geq \varepsilon \tag{6}$$

$$\sum_{k=1}^{L} r_{ik} \geq R_{t,i} \tag{7}$$

$$0 \leq \sum_{k=a}^{b} p_{i,k} \leq P_i \quad (1 \leq a \leq b \leq L \text{ and } p_{i,k} \neq 0) \quad (8)$$

The target of problem (4) is to maximize the throughput of the hybrid network. Formula (5) reflects the mapping from SINR to transmit rate, which can be done by LTE link-level simulation. Formula (6) reflects the Packet Error Rate (PER) limit of service while formula (7) means the total rate of user i is targeted to be greater than the Guaranteed Bit Rate (GBR) of service demand. Formula (8) is the power and resource allocation constraints of LTE uplink, which must ensure the allocated RBs are continuous and total power not beyond the maximum power of User Equipment (UE).

Based on the constraints, we focus on how to meet various service demands in the hybrid network. Though many studies prove the advantages of D2D communication, there are still two challenges for mode selection: which mode brings the highest capacity gain and whether the selected mode can meet QoS requirements. Since the problem (4) is a non-convex optimization problem, it is difficult to find the optimal result. Hence, we give a practical criterion for the first problem and propose a joint mode selection and resource allocation scheme for the second one. In section IV, we discuss the algorithm to design the sub-optimal scheduling method with system and QoS constraints.

B. Mode Selection Criterion

In this section, we give a criterion to measure the capacity gain and find a solution to select the best resource-sharing pair. We first assume the D2D user j works in underlay mode, and consider a certain cellular user i to measure the sharing rate gain.

The original SINR of cellular user i is

$$\beta_{c,ik} = \frac{p_{ik}/PL_{b,ik}}{n_b + IoT} \quad (9)$$

The new SINR of cellular user sharing resource with the underlay D2D user is

$$\beta'_{c,ik} = \frac{p_{ik}/PL_{b,ik}}{n_b + IoT + p_{jk}/PL_{b,jk}} \quad (10)$$

SINR of the target D2D user can be expressed by

$$\beta'_{d,jk} = \frac{p_{jk}/PL_{u,jjk}}{n_b + IoT + p_{ik}/PL_{u,ijk}} \quad (11)$$

The rate gain on RB k can be calculated using Shannon's well-known formula:

$$H(p_{jk}) = B_i[log(1+\beta'_{c,ik}) + log(1+\beta'_{d,jk}) - log(1+\beta_{c,ik})] \quad (12)$$

Note that p_{ik}, PL and IoT are independent values with the scheduled D2D user j and $H'(p_{jk}) \geq 0$, which means $H(p_{jk})$ will reach the peak level when p_{jk} is at the end points of its feasible zone. Considering the rate and PER limits of QoS requirement, we can obtain a target SINR $\beta_{t,i}$ for cellular user i. Since we must ensure $\beta'_{c,ik} \geq \beta_{t,i}$, the transmitting power P^*_{jk} which leads to the maximum capacity gain is limited to only 3 elements in the set $0 \leq p_{jk} \leq P_{max}$:

$$P^*_{jk} \in \left\{0, min(PL_{b,jk} \cdot \frac{p_{ik}}{PL_{b,ik} \cdot \beta_{t,i}}, P_{max})\right\} \quad (13)$$

For certain underlay D2D user, we can utilize formula (12) and (13) to calculate capacity gain on all feasible resource blocks and allocate the best group which maximizes system capacity. Similarly, when idle resources are available in current system, the old rate is ignored and capacity gain is only measured by the maximum rate of the scheduled D2D user. Furthermore, when a sharing pair is selected, mode selection process is also completed: if $P^*_{jk} = 0$, user j should select dedicated mode and occupy RBs with no cellular user, while if $P^*_{jk} \neq 0$ user j will choose underlay D2D mode and share RB k with the dedicated user who maximizes the rate gain.

IV. Joint Mode Selection and Resource Allocation (JMSRA) Scheme

Considering a hybrid network with multiclass services, mode selection problem becomes an optimization process with QoS and fairness constraints. In this paper, we propose two scheduling schemes for dedicated users and underlay users, called joint mode selection and resource allocation (JMSRA) schemes. The DMSRA scheme is designed for dedicated users, including cellular users and dedicated D2D users, while the UMSRA scheme is for underlay users, who share resources with other dedicated or underlay users. In addition, we define a mode transfer rule to dynamically adapt to the QoS requirement of each user.

In JMSRA scheme, users are divided into two sets, i.e., S_d for dedicated users and S_u for underlay users. In the initialization phase, cellular users and D2D users with poor direct-link gain are added to S_d while other D2D users are classified into S_u. To measure channel state, the received SINR of cellular link is compared with that of direct link. If cellular link performs better, transmitting via BS may be a good choice when service history (e.g. delay, average rate) is not available to the scheduler. However, when the scheduler has a good knowledge of service history, communication mode should be selected dynamically according to mode transfer rules.

Algorithm 1 describes in detail the resource allocation scheme and mode transfer process in DMSRA algorithm. After the initialization phase, the scheduler assigns RBs in sequential order. In each scheduling loop, the scheduler assigns feasible RBs to the user with highest priority, which can be calculated by Proportional Fair (PF) function Q_d with service modified factors A^* [8] (if A^* is not available at the beginning, priority is randomized). In this way, each RB group will be allocated to the best matched user. Finally, the scheduling process is terminated when all the RBs are allocated or users with requests are all scheduled. In case the number of RBs is not enough, the remaining users are still waiting for resources, then the scheduler will add these users into S_u to provide opportunities for underlay D2D communication. That means unscheduled users will not wait until next scheduling slot and system efficiency will increase.

Algorithm 1 DMSRA Algorithm

Initialization
$U_{RB} \leftarrow$ set of unassigned resource blocks
$S' \leftarrow$ set of UE_i waiting to transmit data and $UE_i \in S_d$
Define $Q_d(i) = A^* \cdot r_i/R_i \quad 1 \leq i \leq N$, where r_i and R_i are instantaneous and average rate for UE_i
$x \leftarrow 1$
while $U_{RB} \neq \phi$ and $S' \neq \phi$ **do**
  for all $UE_i \in S'$ **do**
    find a feasible RB group $[RB_x, RB_{y_i}]$ and calculate the priority of UE_i with function Q
  end for
  Assign the feasible RB group ($[RB_x, RB_{y_{i*}}]$) to UE_{i^*} with highest priority
  $U_{RB} \leftarrow U_{RB} \setminus \{RB_x, \ldots, RB_{y^*}\}$
  $S' \leftarrow S' \setminus \{UE_{i^*}\}$, $x \leftarrow y^* + 1$
end while
if $S' \neq \phi$ **then**
  $S_d \leftarrow S_d \setminus S'$, $S_u \leftarrow S_u \cup S'$
end if

UMSRA scheme is designed for underlay users to choose the best RB group in available resources. The scheduling process is shown in Algorithm 2. After the initialization phase, each user in S_u is measured and scheduled in descending order of Q_u, which ensures the fairness among users. Since the scheduler can record average rate and delay for each user, it will give higher priority to users with poor satisfaction and channel state ($PL_{u,ii} \geq PL_{b,i}$). When selecting the best RB group for UE_{i*}, capacity gain in formula (12) is utilized as a criterion. If there is no dedicate user on the feasible RB group, the scheduler decides the best link mode for UE_{i*}, which can be measured by the received SINR of cellular link and direct link, otherwise UE_{i*} will choose underlay D2D mode and limit the transmit power to avoid interference to the cellular link. If there is no feasible RB group meeting the throughput requirement, UE_{i*} will be added to S_d and have a high fairness priority among dedicated users. After executing DMSRA and UMSRA scheme in sequence, the scheduler considers the service state of each user, and changes its communication mode or link mode if necessary. Since resource allocation is based on QoS and fairness requirements, JMSRA scheme performs better than simple scheduling schemes that do not consider mode selection and service demands, especially in heavy load and terrible interference environment.

V. Performance Analysis

In this part, system level simulations are carried out to analyze the performance of the proposed schemes. The results are compared to Pure Cellular communication mode case and hybrid mode case with static scheduling schemes (D2D mode is set individually for users with D2D probability).

Algorithm 2 UMSRA Algorithm

Initialization
$S'' \leftarrow$ set of UE_i waiting to transmit data and $UE_i \in S_u$
Define $Q_u(i) = delay^i \cdot PL_{u,ii}/PL_b, i \quad 1 \leq i \leq N$
Sort the values of Q_u in descending order
while $S'' \neq \phi$ **do**
  Set i^* to the index of the ith value of Q_u
  for all feasible RB group $[RB_x, RB_y]$ which can meet rate requirement of UE_{i^*} **do**
    if there'is no dedicated user on $[RB_x, RB_y]$ **then**
      $m_{i^*} \leftarrow$ arg max$SINR_{i^*}$
    else
      $m_{i^*} \leftarrow 1$ (set underlay D2D mode)
    end if
    Calculate the capacity gain of UE_{i^*} on $[RB_x, RB_y]$
  end for
  if max capacity gain ≥ 0 **then**
    Assign ($[RB_x, RB_{y_{i^*}}]$) with highest gain to UE_{i^*}
    Update interference level on $[RB_x, RB_{y*}]$ with UE_{i^*}
  else
    $S_u \leftarrow S_u \setminus \{UE_{i^*}\}$, $S_d \leftarrow S_d \cup \{UE_{i^*}\}$
  end if
  $S'' \leftarrow S'' \setminus \{UE_{i^*}\}$
end while

TABLE I
SIMULATION PARAMETERS

Parameter	Setting
System Bandwidth	10MHz
Cellular Layout	19 cells, 3 sector per cell
System Area	radius of cell is 500m
Number of users per cell	10,20,30,40,50
Noise Figure	5 dB at BS / 9 dB at UE
Max Transmit Power	24 dBm (dedicated user) / 10 dBm (underlay user)
Path loss for cellular link	$36.7 + 35 \lg d$
Path loss for direct link	$31.54 + 40 \lg d$
Probability of D2D link	0.2 to 0.5
Max D2D link distance	10,30,50

A. Simulation Assumptions and Parameters

We develop a multi-cell system-level simulation platform based on our previous work[9]. The probability for D2D communication is given as a simulation parameter according to UE's inner path loss. Devices without D2D probability are distributed uniformly in their active cells, while each D2D pair distributes in a disk with distance limit. The path loss for cellular link is calculated by COST-231 Hata Model as suggested in [9], and the path loss for D2D link is calculated by modified model for short-range communications. Other system parameters are listed in Table 1.

TABLE II
QoS REQUIREMENTS

Services	Delay budget	Rate budget	PER rate
VoIP	50ms	16Kbps	10^{-3}
Web	300ms	256Kbps	10^{-6}
Ftp	300ms	1-2Mbps	10^{-6}

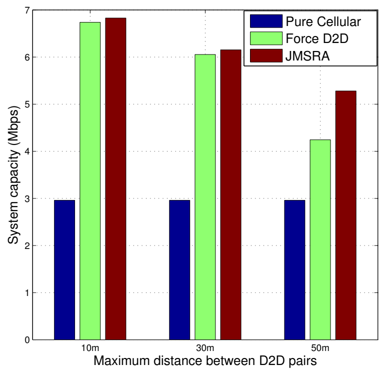

Fig. 2. System capacity of when user number is 50 and D2D probability is 0.4. Maximum distance between D2D pairs varies from 10m to 50m.

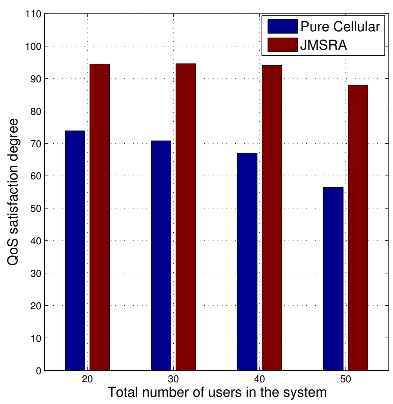

Fig. 3. Satisfaction of service when user number is 20,30,40 and 50, which is measured by the ratio of number of users meeting QoS requirements to total user number. Maximum distance between D2D pairs is 50m.

B. Numerical Results

Simulation results show that system capacity of JMSRA algorithm and Force D2D scheme is much higher than Pure Cellular scheme when channel quality of the direct link is quite good. However, although underlay D2D communication increases sum-rate by reusing space resources, the capacity gain decreases with the increasing distance between D2D pairs, as can be seen from Fig. 2. In this case, JMSRA scheme can be aware of current channel state and adaptively select the best mode for each user, which leads to around 24% better performance than Force D2D scheme when maximum distance is 50 meters.

Fig. 3 shows service satisfaction degree performance with increasing system loads. Satisfaction degree is measured by the ratio of number of users meeting QoS requirements to total user number of the system. Since JMSRA scheme considers QoS requirements and service states when optimizing communication mode vector, the satisfactory degree stays in a high level, even when the number of users increases to 50. Therefore, JMSRA is an effective scheme to allow D2D communication for reducing system load in a large user pool.

VI. Conclusion

In this paper, we analyze system equations and constraints of QoS requirements in the hybrid network. Furthermore, we utilize the equations and propose a dynamic scheduling scheme, which can adaptively select link mode and allocate resources according to users' service demands and interference level. Numerical analysis shows that JMSRA scheme can achieve higher system capacity than both Pure Cellular and Force D2D scheme, especially when system load is heavy and channel condition between direct communicating devices is poor. Considering the best link mode and resources in D2D communication, JMSRA scheme results in a high capacity gain and satisfaction degree.

References

[1] Lei Lei, Zhangdui Zhong, Chuang Lin, Xuemin Shen, “Operator controlled device-to-device communications in LTE-advanced networks,” *IEEE Wireless Communications*, Jun. 2012, Vol. 19, No. 3, pp. 96-104.

[2] Peng Cheng; Lei Deng; Hui Yu; Youyun Xu; Hailong Wang, “Resource allocation for cognitive networks with D2D communication: An evolutionary approach,” *Wireless Communications and Networking Conference (WCNC)*, Apr. 2012, pp. 2671-2676.

[3] D. Tsolkas, E. Liotou, N. Passas, L. Merakos, “A graph-coloring secondary resource allocation for D2D communications in LTE networks,” *International Workshop on Computer Aided Modeling and Design of Communication Links and Networks*, Sept. 2012, pp. 56-60.

[4] G. Fodor, N. Reider, “A Distributed Power Control Scheme for Cellular Network Assisted D2D Communications,” *Global Telecommunications Conference (GLOBECOM 2011)*, Dec. 2011, pp. 1-6.

[5] C.H. Yu, O. Tirkkonen, K. Doppler, and C. Ribeiro, “Power Optimization of Device-to-Device Communication Underlaying Cellular Communication,” *Communications, 2009. ICC '09. IEEE International Conference on*, pp1-5.

[6] Liu, Ziyang; Peng, Tao; Xiang, Shangwen; Wang, Wenbo, “Mode selection for Device-to-Device (D2D) communication under LTE-Advanced networks,” *Communications, 2012. ICC '12. IEEE International Conference on*, Jun. 2012, pp. 5563-5567.

[7] K. Doppler, C.-H. Yu, C. Ribeiro, P. Janis, “Mode Selection for Device-To-Device Communication Underlaying an LTE-Advanced Network,” in *Wireless Communications and Networking Conference*, Apr. 2010, pp. 1-6.

[8] H. Lei, C. Fan, X. Zhang, and D. Yang, “QoS Aware Packet Scheduling Algorithm for OFDMA Systems,” *IEEE 64th Vehicular Technology Conference (VTC Fall '07)*, Oct. 2007, pp. 1877-1881.

[9] Li Chen, Wenwen Chen, Bin Wang, Xin Zhang, Hongyang Chen, and Dacheng Yang, “System-Level Simulation Methodology and Platform for Mobile Cellular Systems,” *IEEE Communication Magazine*, 2011, Vol. 49, No. 7. pp. 148-155.