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Citation: SCIENCE CHINA Information Sciences **58**, 082301(7) (2015); doi: 10.1007/s11432-014-5201-x

View online: http://engine.scichina.com/doi/10.1007/s11432-014-5201-x

View Table of Contents: http://engine.scichina.com/publisher/scp/journal/SCIS/58/8

Published by the Science China Press

SCIENCE CHINA
Information Sciences

• RESEARCH PAPER •

August 2015, Vol. 58 082301:1–082301:7
doi: 10.1007/s11432-014-5201-x

Using full duplex relaying in device-to-device (D2D) based wireless multicast services: a two-user case

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Received June 15, 2014; accepted August 6, 2014; published online December 17, 2014

Abstract D2D communication has been proposed as an important supplement to the existing centralized cellular networks which allows two physically adjacent cellular user equipments (UEs) to communicate directly. This paper concerns using D2D to improve wireless multicast services in cellular networks. Specially, we consider a D2D transmitter UE can act as a full-duplex (FD) relay to assist a cellular multicast from a base station (BS) to a group of two UEs. And a new scheme which allows an intra-cell D2D retransmission to underlay a cellular multicast is proposed. Under the constraint of the minimum signal-to-interference-and-noise ratio (SINR) required by each of the receiver UEs, the aim of the scheme is to select the best UE in a multicast group to perform the D2D retransmission with the serving BS. Thus, the aggregate transmit power consumed at the BS and at the selected UE can be minimized. The numerical results show that the proposed scheme outperforms traditional cellular multicast scheme as it consumes less transmit power to achieve the same SINR target at the receiver UEs.

Keywords D2D communication, cellular multicast, full-duplex relaying, power control, interference management

Citation Zhang G P, Yang K, Liu P, et al. Using full duplex relaying in device-to-device (D2D) based wireless multicast services: a two-user case. Sci China Inf Sci, 2015, 58: 082301(7), doi: 10.1007/s11432-014-5201-x

1 Introduction

In cellular networks, wireless multicast [1] is a spectrum efficient way to deliver the same content to multiple UEs simultaneously. Since the receiver UEs always experience different channel conditions, the data rate of a cellular multicast has to be selected according to the worst channel condition of the UEs. Otherwise, a high transmit power is needed at the cellular multicast sender (i.e., a BS) to meet the minimum SINRs required by the UEs to ensure successful reception. This leads to the significant degradation of the achievable rate or the energy efficiency of a cellular multicast, particularly when most (but not all) receiver UEs are in good channel conditions, as one or very few UEs with poor channel conditions (e.g., the UEs at cellular border) may become the bottleneck for the multicast.

Recently, under the scope of 3GPP LTE-A, D2D communication has been regarded as an effective technique to provide better local service in cellular networks [2]. By enabling proximate cellular UEs to

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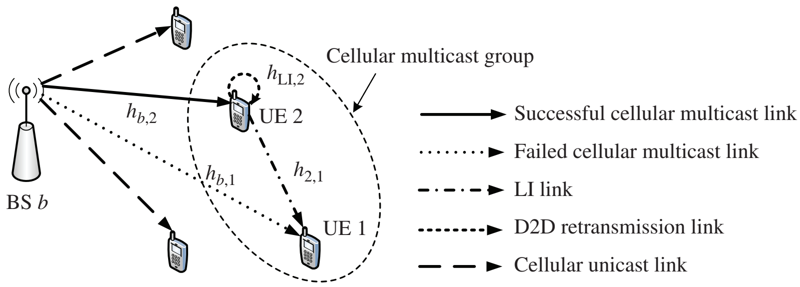

Figure 1 FD relaying based D2D retransmission model.

communicate directly instead of conveying data via the serving BS, D2D may achieve higher data rates, lower power consumption, and more efficient resource utilization [3]. Many researchers focus on utilizing D2D to improve cellular multicast service. As reported in [4–6], multiple proximate UEs which subscribe the same multicast service can be formed as a multicast group under the control of the serving BS. If some of the UEs which correctly decode the multicast data from the BS can retransmit the data to the UEs which fail to decode, the data rate and energy efficiency of the cellular multicast could be improved significantly. In what follows, we refer to the UEs which successfully decode from a cellular multicast as the candidate D2D transmitter UEs (TUEs), and the UEs which fail to decode as the D2D receiver UEs (RUEs). In [4], the authors propose that all candidate TUEs should perform the D2D retransmission by broadcasting their received data on the same frequency-band. Although it can achieve high multicast rate with low signaling overhead, a large number of redundant D2D retransmissions may lead to a low energy efficiency and strong mutual interference. In [5], the authors suggest assigning the D2D retransmission task to a fixed number of TUEs. Unfortunately, they do not deal with the issue of how to select the reliable TUEs from the candidates to perform the D2D retransmission. As a major advancement to [4,5], the authors in [6] propose a D2D retransmission scheme which can adaptively select the optimal number of reliable TUEs to perform cooperative multicast with the serving BS and can achieve optimized resource utilization. However, the authors in [6] only considered the half duplex (HD) relaying approach which relies on orthogonal spectrum allocation (OSA) between a cellular multicast and a D2D retransmission. Although OSA eases the task of interference management, better resource utilization may be achieved by the usage of non-orthogonal spectrum allocation (NOSA) [3], which allows cellular multicasts and D2D retransmissions to take place over the same frequency-band simultaneously.

According to the previously mentioned analysis, in this paper, a D2D based cellular multicast scheme is proposed which allows NOSA between a cellular multicast and a D2D retransmission. In particular, we resort to the FD relaying approach [7] which can achieve higher spectrum reuse-gain than HD relaying. As the first step of the research, we focus on a two-user cellular multicast model as in [8,9]. By jointly optimizing the transmit powers at the cellular multicast sender BS and the selected D2D transmitter UE, the proposed scheme can reduce the aggregate power consumption while satisfying the target SINRs required by the receiver UEs.

The rest of this paper is organized as follows. In Section 2, we describe the considered two-user cellular multicast model. In Section 3, we introduce traditional cellular multicast scheme which is used as the baseline of this study. In Section 4, we propose our FD relaying based D2D retransmission scheme and derive the optimal power allocation in closed-form. In Section 5, we provide the numerical results. Finally, in Section 6, we conclude the paper.

2 System model

The two-user cellular multicast model [9], illustrated in Figure 1 was considered. Under the control of the serving BS b, two adjacent UEs 1 and 2, which require the same content are to be formed as a multicast group. BS b continues broadcasting a sequence of data packets to UEs 1 and 2. We assume that the channels in the system are frequency-flat slow fading, which remain constant for the duration of at least one packet transmission and can change to a new independent realization for the next packet transmission.

In the following analysis, we assume that UE i, $\forall i \in \{1, 2\}$, is designated as the D2D transmitter which operates in the FD relaying mode [7]. Thus, UE i can successfully receive data from the cellular multicast of BS b and is responsible for retransmitting the received data to the other receiver UE, i.e., UE i, $\forall i \in \{1, 2\}$, and $j \neq i$. Since FD relaying is used, the reception and retransmission at UE i can take place on the same frequency-band simultaneously. For that purpose, it is ordered that UE i should be equipped with isolated receive and transmit antennas. Hence, the severe loop interference (LI) at UE i resulting from the D2D retransmission to the cellular reception can be sufficiently mitigated [7]. As shown in Figure 1, we denote the channel response from BS b to UE i by $h_{b,i}$, the channel response from UE i to UE j by $h_{i,j}$. Due to imperfect cancellation, we denote the residual LI channel at UE i by $h_{\mathrm{LI,i}}$. Let σ^2 denote the variance of the zero-mean additive Gaussian white noise (AGWN) at each receiver UE. We can define the channel-to-noise ratios (CNRs) at the receiver UEs as

$$g_{b,i} = \frac{h_{b,i}^2}{\sigma^2},\ g_{i,j} = \frac{h_{i,j}^2}{\sigma^2} \text{ and } \mathrm{g}_{\mathrm{LI},i} = \frac{h_{\mathrm{LI},i}^2}{\sigma^2},\ i \neq j. \tag{1}$$

In this paper, the performance of traditional cellular multicast is used as the baseline. In traditional cellular multicast, each receiver UE is with a minimum SINR threshold for successful decoding. For simplicity, we assume that UEs 1 and 2 in a multicast group are with the same SINR threshold Γ. Let $p_{b,i}^{\mathrm{C}}$ denote the transmit power at BS b to satisfy the target SINR of UE i, $\forall i \in \{1, 2\}$. Thus, the following SINR constraint must be satisfied at UE i.

$$p_{b,i}^{\mathrm{C}} g_{b,i} \geqslant \Gamma,\ \forall i \in \{1, 2\}. \tag{2}$$

As the minimum multicast power at BS b is determined by the worst channel condition of the receiver UEs by ignoring the greater than condition in (2), we can derive the minimum multicast power required at BS b as

$$P_{\mathrm{C}} = \max\left(p_{b,i}^{\mathrm{C}}, p_{b,j}^{\mathrm{C}}\right) = \max\left(\frac{\Gamma}{g_{b,i}}, \frac{\Gamma}{g_{b,j}}\right),\ i \neq j. \tag{3}$$

The result in (3) will be used for comparison purpose in the simulation part.

3 D2D retransmission based cellular multicast scheme

In this section, we focus on using FD relaying based D2D retransmission to improve the energy efficiency of traditional cellular multicast. It is shown in [10] that most of the benefits of cooperative relaying can be achieved with minimum overhead if a single best relay node can be selected to cooperate with the source node. So we consider that one of the UEs in a multicast group (e.g., UE i) is designated as the group head, which performs the intra-group D2D retransmission. Hence, the received SINR at UE i is given by

$$\gamma_{b,i} = \frac{p_{b,i}^{\mathrm{D}} g_{b,i}}{p_i^{\mathrm{D}} g_{\mathrm{LI},i} + 1},\ \forall i \in \{1, 2\}, \tag{4}$$

where $p_{b,i}^{\mathrm{D}}$ represents the transmit power at BS b when UE i is designated as the D2D transmitter and p_i^{D} represents the retransmit power at UE i.

After successfully receiving from the cellular multicast of BS b, we assume that UE i acting as the D2D transmitter will adopt the decode-and-forward (DF) protocol [7] to retransmit the received information to UE j. And UE j will treat the signals retransmitted from UE i as interference when decoding directly from the cellular multicast, or it will treat the signals transmitted from BS b as interference when decoding indirectly from the D2D retransmission. Accordingly, we can express the SINRs received at UE j as

$$\gamma_{b,j} = \frac{p_{b,i}^{\mathrm{D}} g_{b,j}}{p_i^{\mathrm{D}} g_{i,j} + 1} \text{ and } \gamma_{i,j} = \frac{p_i^{\mathrm{D}} g_{i,j}}{p_i^{\mathrm{D}} g_{b,j} + 1},\ i \neq j, \tag{5}$$

respectively, where $\gamma_{b,j}$ represents the SINR received at UE j when it decodes from the cellular multicast, and $\gamma_{i,j}$ represents the SINR received at UE j when it decodes from the D2D retransmission.

Under the constraint of satisfying the minimum SINR requirement at each receiver UE, our aim is to select the optimal UE in a multicast group to perform the cooperative retransmission with the serving BS, which can minimize the aggregate power consumed at the BS and at the selected UE. The combined problem of the optimal D2D transmitter selection and the optimal power allocation can be formulated as

$$i^* = \text{argmin}_{\forall i\in\{1,2\}} P_i^{\rm D},\ P_i^{\rm D} = p_{b,i}^{\rm D} + p_i^{\rm D}, \tag{6}$$

$$\text{subject to}: \gamma_{b,i} = \Gamma, \forall i \in \{1,2\}, \tag{6-1}$$

$$\gamma_j = \max\{\gamma_{b,j}, \gamma_{i,j}\} = \Gamma,\ \forall i,j \in \{1,2\} \text{ and } i \neq j. \tag{6-2}$$

Note that to solve problem (6) in closed-form, we have ignored the greater than condition in constraints (6-1) and (6-2). Thus the solution will achieve the lower-bound of the performance of the proposed scheme.

3.1 Optimal power allocation

First, it is necessary that the multicast information from BS b should be successfully received at the D2D transmitter, i.e., UE i. By inspecting (4), we can derive

$$\gamma_{b,i} = \frac{p_{b,i}^{\rm D} g_{b,i}}{p_i^{\rm D} g_{{\rm LI},i} + 1} = \Gamma,\ \forall i \in \{1,2\}. \tag{7}$$

Thereafter, due to the D2D retransmission from UE i, UE j should determine whether decoding is from the cellular multicast or from the D2D retransmission. By inspecting (5), we can further analyse problem (6) in the following two cases.

Case 1: In the case of UE j, if the SINR received from the cellular multicast just reach the SINR threshold Γ, i.e.,

$$\gamma_{b,j} = \frac{p_{b,i}^{\rm D} g_{b,j}}{p_i^{\rm D} g_{i,j} + 1} = \Gamma,\ i \neq j. \tag{8}$$

UE j will decode from the cellular multicast even when $\gamma_{i,j} > \gamma_{b,j}$, which can be explained as follows. The signal processing at a D2D transmitter will induce a delay of several symbol times to guarantee the non-correlation between the retransmitted symbol and the received symbol (from the multicast of the serving BS) in each time instant. So, if (8) is satisfied, UE j prefer to receive directly from the cellular multicast, and, thus, reduces the delay.

In such a case, by solving (7) and (8), we can derive the optimal transmit power allocated to BS b and the D2D transmitter, i.e., UE i, as

$$p_{b,i}^{\rm D,Case1} = \Gamma\frac{(g_{b,j} - \Gamma g_{i,j}) + \Gamma g_{\rm LI,i}}{g_{b,i}(g_{b,j} - \Gamma g_{i,j})} \text{ and } p_i^{\rm D,Case1} = \frac{g_{b,j} - \Gamma g_{i,j}}{\Gamma}. \tag{9}$$

By inspecting (9), we note that to ensure $p_{b,i}^{\rm D,Case1} > 0$ and $p_i^{\rm D,Case1} > 0$, the condition $g_{b,j} > \Gamma g_{i,j}$ should be satisfied. It indicates that if the SINR threshold Γ for successful decoding is greater than 0 dB (it is the common case when the expected bit error rate (BER) is less than 10^{-3} [11]), Case 1 can only take place when the cellular multicast channel $g_{b,j}$ is much better than the relay channel $g_{i,j}$.

Case 2: For UE j, if the SINR received from the D2D retransmission just reaches the threshold and is greater than the SINR received from the cellular multicast, we then have

$$\gamma_{i,j} = \frac{p_i^{\rm D} g_{i,j}}{p_{b,i}^{\rm D} g_{b,j} + 1} = \Gamma \text{ and } \gamma_{i,j} > \gamma_{b,j},\ i \neq j. \tag{10}$$

In such a case, UE j can only decode from the D2D retransmission. By solving (7) and $\gamma_{i,j} = \Gamma$ in (10), we can derive the optimal transmit power allocated to BS b and the D2D transmitter, i.e., UE i, as

$$p_{b,i}^{\rm D,Case2} = \frac{\Gamma(g_{{\rm LI},i} + \Gamma g_{i,j})}{g_{b,i}g_{i,j} - \Gamma^2 g_{{\rm LI},i} g_{b,j}} \text{ and } p_i^{\rm D,Case2} = \frac{\Gamma(g_{b,i} + \Gamma g_{b,j})}{g_{b,i}g_{i,j} - \Gamma^2 g_{{\rm LI},i} g_{b,j}}. \tag{11}$$

As in Case 1, it is essential that $p_{b,i}^{\mathrm{D,Case2}} > 0$ and $p_{i}^{\mathrm{D,Case2}} > 0$. These can be guaranteed only when the relay channels for UE j (i.e., $g_{b,i}$ and $g_{i,j}$), the LI channel at UE i (i.e., $g_{\mathrm{LI},i}$) and the SINR threshold Γ have the following relation

$$g_{b,i}g_{i,j} > \Gamma^2 g_{\mathrm{LI},i}g_{b,j},\ \ i \neq j. \tag{12}$$

Next, we investigate the relationship between $\gamma_{i,j}$ and $\gamma_{b,j}$ when the optimal power allocation ($p_{b,i}^{\mathrm{D,Case2}}$, $p_{i}^{\mathrm{D,Case2}}$) is feasible and the expected BER at each receiver UE is less than 10^{-3}, i.e., $\Gamma > 0$ dB [11]. Let $G = \gamma_{i,j} - \gamma_{b,j}$. Then we have

$$G = \Gamma \frac{(g_{b,i}g_{i,j} - \Gamma^2 g_{\mathrm{LI},i}g_{b,j}) + (\Gamma g_{b,j} + g_{b,i})}{(g_{b,i}g_{i,j} - \Gamma^2 g_{\mathrm{LI},i}g_{b,j}) + \Gamma g_{b,i}g_{i,j} + \Gamma^2 g_{i,j}g_{b,j}}. \tag{13}$$

By inspecting (13), if the relay channel from the D2D transmitter, i.e., UE i, to UE j is better than the multicast channel, we will have $\Gamma g_{i,j} > g_{b,j}$. Then, $G > 0$, i.e., $\gamma_{i,j} > \gamma_{b,j}$ can be guaranteed.

However, if a feasible power allocation cannot be found either in Case 1 or in Case 2, it indicates that UE i is not suitable for acting as the D2D transmitter. In such a situation we should test another UE in the multicast group to check whether it is suitable by using the same method as as for UE i. If not again, all the UEs in the group can only decode from the cellular multicast, i.e., operate in traditional cellular multicast scheme [12,13]. In such a situation, there will be no interference resulting from the relaying of the UEs.

3.2 Optimal D2D transmitter selection

In a multicast group, each UE has an opportunity to become the D2D transmitter. Assuming that UE i is finally designated as the D2D transmitter, the minimum aggregate power consumed at the serving BS and at UE i can be denoted by

$$P_i^D = \min\left(p_{b,i}{}^{\mathrm{D,Case1}} + p_i^{\mathrm{D,Case1}}, p_{b,i}{}^{\mathrm{D,Case2}} + p_i^{\mathrm{D,Case2}}\right). \tag{14}$$

Then, the optimal D2D transmitter selection can thus be determined by solving the following problem

$$i^* = \mathrm{argmin}_{\forall i \in \{1,2\}} P_i{}^{\mathrm{D}}. \tag{15}$$

The joint optimal power allocation and optimal D2D transmitter selection problem can be solved at the serving BS in a centralized manner but the global channel state data (CSI) is required [14]. Through a dedicated feedback channel, e.g., the cognitive pilot channel (CCC) proposed by the E2R2/E3 consortium in [15], the CSI can be reliably conveyed between the BS and the distributed 3 UEs.

4 Numerical results

The simulated system is illustrated in Figure 1. To show the high energy efficiency of the proposed D2D retransmission based cellular multicast scheme, we choose traditional cellular multicast scheme as the reference comparison. In the following simulation, we assume that the SINR threshold (for successful decoding) for each UE is $\Gamma = 5$ dB.

First, we show the impact of the LI (at UE 2) on the system energy efficiency. For that purpose, we set $g_{b,2} = 5$ dB, $g_{b,1} = -5$ dB, and $g_{2,1} = 6$ dB. And we increase $g_{\mathrm{LI},2}$ from -5 dB to 5 dB. Under the simulation setting, the minimum multicast power P^{C} required at BS b is 10 W in traditional cellular multicast scheme. The aggregate power assumption P^{D} and the optimal powers $p_{b,2}^D$ and p_2^D allocated to BS b and the D2D transmitter in the proposed scheme are shown in Figure 2, respectively.

From Figure 2, we can observe that the proposed scheme consumes less aggregate transmit power than traditional cellular multicast scheme when $g_{\mathrm{LI},2} \leqslant 3$ dB. It indicates that the proposed scheme can greatly improve the system energy efficiency of cellular multicast (nearly 2 times when $g_{\mathrm{LI},2} \leqslant -2$ dB). In addition, we also observe that in order to invoke the FD-relaying based D2D retransmission, the LI at

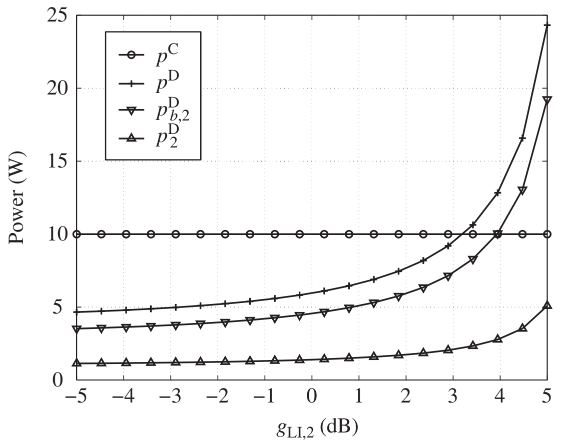

Figure 2 The optimal power allocation in the proposed scheme.

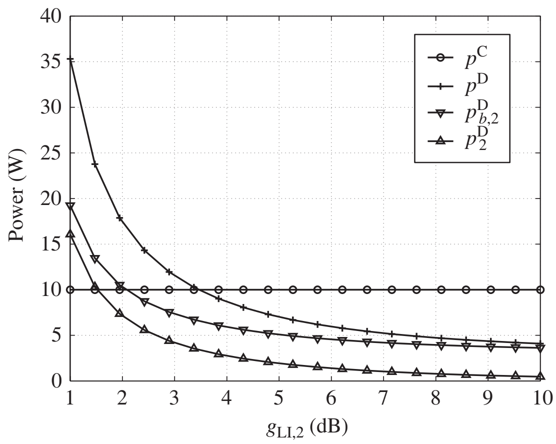

Figure 3 The optimal power allocation in the proposed scheme.

the D2D transmitter should be controlled at a certain level ($g_{\rm LI,2} \leqslant 3$ dB for this case). It ensures the D2D transmitter has the potential to help fulfill the SINR requirement of the other receiver UEs.

Next, we show the impact of the relay channel on the system energy efficiency. For that purpose, we set $g_{b,2} = 5$ dB, $g_{b,1} = -5$ dB, and $g_{\rm LI,2} = 0$ dB, and we increase $g_{2,1}$ from 1 dB to 10 dB. Under this simulation setting, the minimum multicast power $P_{\rm C}$ required at BS b is also 10 W in traditional cellular multicast scheme. The aggregate transmit power assumption $P_{\rm D}$ and the optimal powers $p^D_{b,2}$ and p^D_2 allocated to BS b and the D2D transmitter in such a case are shown in Figure 3, respectively.

From Figure 3, we can observe that the proposed scheme consumes less aggregate transmit power than traditional cellular multicast scheme when $g_{2,1} \geqslant 4$ dB. This indicates that the proposed scheme can greatly improve the system energy efficiency of cellular multicast (nearly 2 times when $g_{2,1} \geqslant 5$ dB). In addition, we also note that to invoke the FD-relaying based D2D retransmission, the relay channel from the D2D transmitter to the receiver UE also plays an important role. Under the simulation setting, $g_{2,1} \geqslant 3.5$ dB is needed.

5 Conclusion

This paper proposes an FD-relaying based D2D retransmission scheme to improve multicast service in cellular networks. It allows a D2D retransmission to underlay a cellular multicast. Then, to achieve the minimum SINR required for successfully decoding at the receiver UEs, the best UE in a two-user multicast group is selected to perform the D2D retransmission with the serving BS. The numerical results show that the proposed multicast scheme outperforms the traditional cellular multicast scheme as it consumes less transmit power to achieve the same SINR at the receiver UEs.

Acknowledgements

The work of Zhang G P, Liu P, Du Y was supported by China Fundamental Research Funds for the Central Universities (Grant No. 2014QNA82), National Natural Science Foundation of China (Grant No. 61471361), and Post-Doctoral Fellowship Program of the China Scholarship Council (Grant No. 2900759643). The work of Yang K was supported by the EU FP7 Projects EVANS (Grant No. GA-2010-269323) and CROWN (Grant No. GA-2013-610524).

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