Full Duplex Device-to-Device Communication in Cellular Networks

Samad Ali
Centre for Wireless Communications
University of Oulu, Oulu, Finland
Email: saali@ee.oulu.fi

Nandana Rajatheva
Centre for Wireless Communications
University of Oulu, Oulu, Finland
Email: rrajathe@ee.oulu.fi

Matti Latva-aho
Centre for Wireless Communications
University of Oulu, Oulu, Finland
Email: matla@ee.oulu.fi

***Abstract*—In this paper we investigate the applicability of in-band full-duplex (FD) radios in device-to-device communication (D2D) in cellular systems. The key challenge in FD radio design is the large self-interference on receiver. It is not possible to completely cancel the self-interference in FD radios. Considering the residual of self-interference, we study the performance of system while D2D link is operating in half-duplex and full-duplex mode. A cellular system is considered while D2D users are exploiting the same resources with cellular users in uplink. We apply a power control method for D2D pair to limit the interference from them on base station. For interference management from cellular transmissions on D2D receivers, interference limited area method is used. Simulation results show that using the most recent FD radios in D2D systems can almost double the throughput of the D2D link.**

***Index Terms* - D2D; underlay; full duplex; inband**

I. Introduction

Wireless communication systems are using frequency division duplex (FDD) or time division duplex (TDD) for two way communcation. In FDD duplex, two nodes use different frequency bands for signal transmission to separate their received signal from their transmitted signal. TDD systems assign different time slots for transmitter and receiver. In each time slot only one user is transmitting. The reason behind is that two nodes cannot communicate at the same time in the same frequency band because of the large self-interference (SI) on one node's receiver from its own transmission. The power of SI is hundreds of thousands times larger that power of signal of interest. This will make it impossible for the receiver to recover the desired signal. The cell sizes in wireless systems are now getting smaller and hence systems are using small transmit powers. Considering this small transmit power and SI cancelation systems, it is possible to design transceivers that are able to transmit and receive at the same time in same frequency band. These systems are called in-band full-duplex (FD) radios. FD radio design has gained considerable attention recently, and several research groups have reported different radios. Different active and passive cancelation techniques have been introduced. In [1] a method of antenna cancelation is presented, which places two transmit antennas in distances of d and $d+\lambda/2$, the received signals from two transmit antennas will have π phase shift and will be added destructively on the receiver. Combined by active analog and digital cancelation techniques, this method provides 60 dB SI cancelation. In [2] authors have studied the characteristics of FD wireless systems and the effects of different passive suppression and active cancelation techniques. MIMO FD (MIDU) has been considered in [3], where authors conclude that the optimal performance can be achieved using the combination of MIMO and FD. A balanced/unbalanced transformer (BALUN) that uses signal inversion lemma to create the inverse of the transmitted signal to be subtracted from received signal which can provide around 45 dB cancelation for 40 MHz bandwidth is investigated in [4]. This system provides 73 dB of SI cancelation and it has no bandwidth or power limitations. Considering around 40 dB path loss between transmit and receive antennas, this system will have more than 100 dB isolation and possible to be used in wi-fi systems. To the best of our knowledge the most recent system that has been implemented is introduced in [5]. This system uses only one antenna and circulator to seperate the received and transmitted signal. Digital and analog techniques are used to cancel 110 dB of SI that is enough to make FD possible in wi-fi systems with transmit power of 20 dBm.

Increased number of users and systems that need wireless communications are leading to congestion of radio spectrum in cellular systems. Therefore effective use of spectrum has become more important and new technologies are required for this purpose. Device-to-device communication (D2D) has been introduced as a key technology to LTE-Advance networks [6]. In D2D, users with short distance and high SINR ratio may directly communicate with each other without going through base station (BS), BS only sends the control signals to these users. These users can either use license exempt bands or licensed bands. In [7] authors have analyzed different resource allocation methods for D2D, where D2D link can use dedicated resource or using resources of one or more than one users. Interference management from D2D communication to cellular users and from cellular communication to D2D link is the main challenge. Power control for D2D link to limit the interference and it's effect on system performance is presented in [8]. Interference limited area resource allocation method for uplink resources is introduced in [9]. In this method an area around the D2D link will be calculated and the resources of the users outside this area will be allocated to D2D link to limit the interference from cellular communication to D2D link.

On the other hand, in small cells that are using D2D

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connection, distance between D2D users should be short and transmit power of the D2D pair will be small. Hence considering the recent work on FD radio design, D2D is a very good candidate to make use of FD radios. With 110 dB of cancelation and maximum transmit power of 20 dBm for D2D and proper resource allocation scheme, cellular systems can have a good performance gain, either in making a better use of spectrum or increasing the system throughput.

In this paper, we consider a cellular system with one D2D link in each cell, D2D users communicate using FD radios. Residual of SI cancelation is considered and performance of FD D2D is studied under different amounts of SI cancelation. Rest of the paper is organized as follows. In section II we present the system model. Details of resource allocation are described in section III. Section IV presents the simulation results. Finally, the conclusion is given in section V.

II. System Model

A. D2D System Model

We consider a cellular system where each cell has M users and one D2D link, K out of M cellular users shown by CU_j will be selected to share their uplink resources with D2D link. In our study we assume that location of the users are known at the BS and D2D users communicate using FD radios. Fig. 1 shows the system model. While D2D users share the same resources as cellular users in uplink, BS receives interference from D2D users transmission. To suppress this interference, we consider a power control scheme similar to that have been used in [9] and [10] which is based on the distance between D2D transmitters and BS. On the other hand D2D receivers suffer from the interference coming from cellular users uplink transmission. To limit this interference, we use the interference-limited-area method proposed at [9]. Areas of A_1 and A_2 around each D2D link are calculated in which the received interference strength is high, and sub-channels of users outside this area will be assigned for D2D link. Calculation of A_1 and A_2 and also the power control method will be explained in section III.

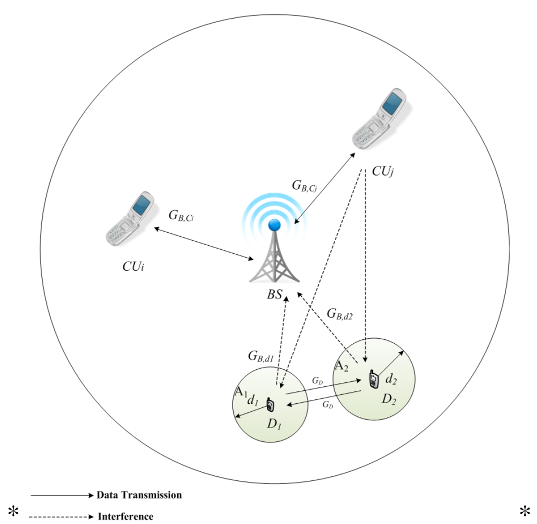

Fig. 1: D2D system model

B. Total Throughput

Throughput of the system in the presence of D2D link is increased, the amount of this gain depends on the resource allocation and power control methods. On other hand, while using FD radios, throughput is affected by the residual of SI. Total throughput of the system when D2D link is activated is:

For half-duplex (HD) D2D:

$$R_{T,HD} = R_C + R_{Cj,HD} + R_{D,HD} \tag{1}$$

For FD D2D:

$$R_{T,FD} = R_C + R_{Cj,HD} + R_{D,FD} \tag{2}$$

In the above equations, R_C is throughput of cellular users that are not sharing resources with D2D users, $R_{Cj,HD}$ and $R_{Cj,FD}$ rate of cellular users that exploit the same resources as D2D users in HD and FD mode respectively. Rate of HD D2D link is $R_{D,HD}$, and for FD D2D we denote the rate by $R_{D,FD}$.

We consider γ_i to be the SNR of CU_i at BS, $\gamma_{j,HD}$ and $\gamma_{j,FD}$ to be the SINR of the cellular users that share the same resources as D2D users while D2D is in HD and FD mode. So the rates for cellular and D2D users are:

$$R_C = \sum_{i=1, i \neq j}^{M} \log_2 (1 + \gamma_i) \tag{3}$$

$$R_{Cj,HD} = \sum_{j=1}^{K} \log_2 (1 + \gamma_{j,HD}) \tag{4}$$

$$R_{Cj,FD} = \sum_{j=1}^{K} \log_2 (1 + \gamma_{j,FD}) \tag{5}$$

When D2D users operate in HD mode, D2D user D_2 is transmitting and D2D user D_1 is receiving. We denote the SINR of D2D user D_l as γ_{Dl}. Rate of the D2D link is:

$$R_{D,HD} = \log_2 (1 + \gamma_{D1}) \tag{6}$$

When D2D users use FD radios, both of D2D users transmit and receive at the same time and the D2D link rate is:

$$R_{D,FD} = \sum_{l=1}^{2} \log_2 (1 + \gamma_{Dl}) \tag{7}$$

In SINR equations for cellular transmissions, we consider P_{ci} to be the transmit power of CU_i and $G_{ci,BS}$ channel gain between CU_i and BS. P_j is the transmit power of cellular user that is using the same resources as D2D users and $G_{j,BS}$ is the channel gain between CU_j and BS, and $I_{Di,cj}$ is interference from D2D transmissions to CU_j.

$$\gamma_i = \frac{P_{ci}.G_{ci,BS}}{N0} \tag{8}$$

SINR for HD mode is:

$$\gamma_{j,HD} = \frac{P_{cj}.G_{cj,BS}}{N_0 + I_{D2,cj}} \tag{9}$$

SINR for FD mode is:

$$\gamma_{j,FD} = \frac{P_{cj}.G_{cj,BS}}{N_0 + I_{D1,cj} + I_{D2,cj}} \tag{10}$$

In the equation for SINR of D2D users, we consider that P_{Dl} and G_D are transmit powers of D2D users and channel gain between them respectively. I_l is the residual of SI at node l which can be written as $I_l = C(0, \sigma_l^2)$ [2], $\sigma_l^2 = \beta P_l$ where β depends on the amount of SI cancelation in the node l . $I_{cj,l}$ is the interference coming from CU_j to D2D user l.

For HD mode we only write the γ_1 :

$$\gamma_1 = \frac{P_{D2}.G_D}{N_0 + \sum_{j=1}^{K} I_{cj,1}} \tag{11}$$

For FD mode:

$$\gamma_l = \frac{P_{Dz}.G_D}{N_0 + I_l + \sum_{j=1}^{K} I_{cj,l}} \quad l, z \in \{1, 2\}, l \neq z \tag{12}$$

N_0 is additive white Gaussian noise in all the equations.

III. Interference management and Resource allocation

In this section, power control for D2D link is explained. D2D transmit powers are controlled so that the interference from their transmission to cellular uplink will be limited. Next we explain the interference-limited-area and resource allocation.

A. D2D power control

We consider that received signal power from cellular users at BS is kept at a constant level P_{RC}, i.e, users have a power control mechanism that depends on their channel gain to the BS. D2D transmissions cause interference on the BS since D2D link is sharing resources with other cellular users. To suppress this interference transmit power of D2D users should be controlled. We propose that D2D users should transmit with a power that interference over signal ratio (ISR) for users that share resources with D2D link at BS should to be smaller than a defined threshold δ_B. ISR at the BS is expressed as:

$$ISR = \frac{P_{Dl}.G_{l,BS}}{P_{RC}} \leq \delta_B \tag{13}$$

where P_{Dl} is the transmit power of D2D user l, $G_{l,BS}$ is channel gain between lth D2D user and BS, and P_{RC} is received power level of cellular users at BS. From Eq. 1 we use the following power for D2D transmitter:

$$P_{Dl} \leq \frac{P_{RC}.\delta_B}{G_{l,BS}} \tag{14}$$

This maximum transmit power for D2D link will guarantee that the SINR of BS does not fall below a defined threshold.

B. Limiting the interference from Cellular users to D2D

While D2D users share the same frequency bands with other cellular users in uplink, D2D receivers receive interference from uplink transmissions of cellular users. In this section we present the interference limited area (ILA) method for selecting a group of users which their sub-channels can be used in D2D link, so that the interference on D2D receivers will not be harmful. In this method, we calculate an area around D2D receivers in which the interference coming from cellular communications will be large. In this work, this area is considered to be a circle with the radios d_i for D2D user D_i. Users outside this area are selected for resource sharing with D2D users. Area in which the ISR for D2D user D_l is larger than δ_{ILA} can be calculated as:

$$ISR_l = \frac{P_{cmax}.G_{ci,Dl}}{P_{Dl}.G_D} > \delta_{ILA} \tag{15}$$

$$G_{ci,Dl} > \frac{P_{Dl}.G_D.\delta_{ILA}}{P_{cmax}} \tag{16}$$

Channel gain between CU_i and D_l can be written as $PL_0.(d_l)^{-\alpha}$, so:

$$PL_0.(d_l)^{-\alpha} > \frac{P_{Dl}.G_D.\delta_{ILA}}{P_{cmax}} \tag{17}$$

The minimum distance to limit the interference to D2D is:

$$d_l < (\frac{P_{cmax}.PL_0}{P_{Dl}.G_D.\delta_{ILA}})^{1/\alpha} \tag{18}$$

In these equations, we assume that P_{cmax} is the maximum transmit power of cellular users and α is the path loss exponent. d_l is the distance to D2D user D_l in meters. Now we have found areas around D2D users A_1 and A_2. All the users that are outside these areas are selected to share the same resources with D2D users.

C. Resource Allocaiton

After we select users by applying interference limited-area-method, we can either use some of the resources or one of them. In this paper we consider two scenarios, first one is when D2D link is using resources of all of the K cellular users. In second scenario D2D selects only one out of K users for resource sharing. We consider the sub-channels of users outside ILA as S_i, one of them is selected shown by S^* that maximizes the total throughput R_T of the system.

$$S^* = \max_{S_i} R_T \tag{19}$$

IV. Simulation Results

In this section we present the simulation results to show under how much of SI cancelation FD radios improve the performance of a D2D link in a practical cellular system. LTE systems employ orthogonal frequency division multiple access (OFDMA) in downlink communication, and single carrier frequency division multiple access (SC-FDMA) in uplink. The bandwidth in LTE is divided into resource blocks (RB). Each resource blocks occupies 180 kHz in frequency domain (equal to 0.5 ms in time domain). Since the minimum uplink scheduling interval in LTE is 1ms, the smallest resource in frequency domain is two resource blocks, i.e 360 kHz. Here we consider a single cell scenario where 30 users are randomly dropped in the cell, two users with less than 25 meters distance are selected as D2D pair. It is assumed that each user has two LTE resource blocks to communicate in uplink and D2D users have to use sub-channels of other cellular users. Table I shows the simulation parameters.

TABLE I: Simulation Parameters

Parameter	Value
Cell Radios	500 m
Maximum D2D Distance	25 m
CUs Per Cell (M)	30
δ_B	0.01
δ_{ILA}	0.01
α	4
Maximum CU transmit power	23 dBm
Noise Figure at BS	2 dB
Noise Figure at CU	9 dB
D2D Path Loss Model	148 + 40log(d[km])
BS to CU Path Loss Model	128.1 + 36.7log(d[km])
Noise spectral density	-174 dBm/Hz

Fig. 2 shows the throughput of the system when only one CU_j is sharing resources with D2D. Throughput of the system with FD D2D will increase as the amount of SI cancelation increases, it can be seen that for less $78dB$ of SI cancelation HD D2D has better performance due to large residual of SI. However as amount of SI cancelation increases, residual of SI will be small and SINR of D2D receivers will increase and FD will outperform HD. At 110 dB cancelation, FD D2D link has almost double throughput of HD D2D.

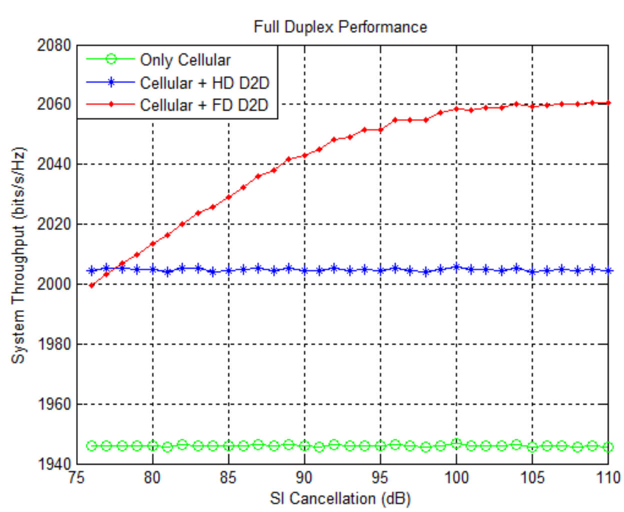

Fig. 2: Throughput of System for one user resource sharing for minimum SNR at BS of 10 dB

In Fig. 3 we present the ratio of FD D2D link rate over HD D2D link rate for two scenarios, fist when D2D is sharing resources with only one cellular user and second when resources of K users are being shared. In second case , FD outperforms HD with lower amount of SI isolation ($69dB$). The reason is that when the number of users that share resources with D2D link is increased, D2D receivers receive more interference and interference plus noise level increases. This makes the effect of residual of SI on SINR of D2D to be less than the case where only one user shares the resources.

Fig. 4 shows the FD D2D over HD D2D ratio versus the SNR target at BS for uplink signals for different SI cancelation amounts. As this SNR target increases, cellular uses can transmit with larger power, this will result in larger transmit power for D2D users also. This will lead to increase in residual of SI as the SNR target increases and FD performance will worsen. In this case, we have applied the case when only one cellular user resources is shared.

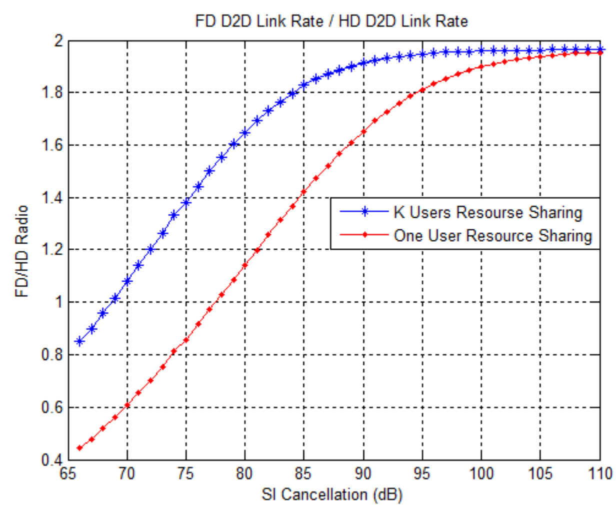

Fig. 3: FD/HD Rate Ratio comparison of one user and K users resource sharing for minimum SNR at BS of 10 dB

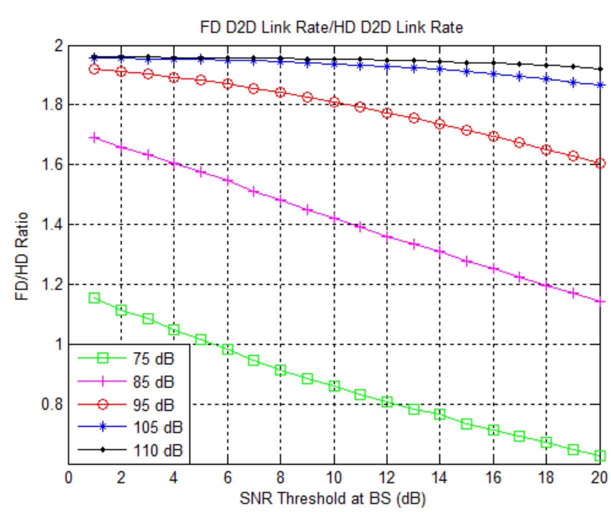

Fig. 4: FD/HD Rate Ratio as a function of minimum SNR at BS for one user resource sharing

V. CONCLUSIONS

We have investigated full-duplex device-to-device communication in cellular systems while D2D users share uplink resources with cellular users. To limit the interference from D2D users to cellular users, power control based on ISR of cellular users is applied. To mitigate the interference from cellular communication to D2D receivers, we have used interference-limited-area method. We calculate an area around each D2D receiver in which if there is a cellular users with the same resources as D2D users, interference amount will be large. Users outside the ILA are selected for resource sharing with D2D link. We consider that D2D link is able to use all the subchannels of users outside ILA. We study two cases, fist when D2D users are sharing all the resources available for them. Second, D2D selects only one users to share resources which maximizes the total throughput of the system. Performance of the system for both HD and FD modes are studied. For FD mode, we have considered different amount of SI cancelation and modeled residual of SI in our formulas. Finally, simulation results show that using the most recent FD radios, D2D link can have alsmost double throughput compared to HD.

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