Full Duplex Device to Device Communication in Cellular Networks

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***Abstract*—In this paper, we investigate the performance improvements of single band full duplex device to device communication that can transmit and received on the same frequency band in cellular networks. In cellular networks, two separate frequencies are used to enable simultaneous transmission and reception for half duplex radios. Recently, full duplex radios that allows a wireless node to simultaneously transmit and receive in one frequency band were proposed. It was shown that it was effective for short-range communications. As such, full duplex communication is adequate for device to device (D2D) communication, which is usually a short range communication. Device to device communication is an underlay scheme for cellular networks that enables peer-to-peer local services with limited impact on the primary cellular network. When user devices are closer to each other than the base station, D2D communication can improve the bandwidth efficiency of the communication between the users. When full duplex communication is adopted for D2D communication, it requires only one frequency band for two way communication between the local users. It improves the bandwidth efficiency for D2D communication. We propose a simple full duplex D2D communication protocol and analyze the bandwidth performance gain of the protocol compared to the legacy cellular communication scheme.**

I. INTRODUCTION

Wireless networks are often limited in either the bandwidth efficiency or energy efficiency. Cellular networks which use a significant amount of infrastructure generally require communication between two users to go through a base station. If the two users are in close proximity this is an inefficient use of the frequency spectrum and energy, especially if the communications involves a substantial amount of data. Device-to-device communications where communications takes place directly between two devices rather than through some infrastructure has the challenge of deciding when device-to-device communication is appropriate and then the design of the appropriate protocol. Device-to-device communication has been included in standards such as IEEE 802.11 in a distributed fashion. In an IEEE 802.11 network, a wireless node senses the channel and decides whether it can send a packet or not. In distributed wireless networks nodes employ a collision avoidance mechanism such as CSMA/CA or RTS/CTS protocol. While an access point (AP) is typically used in an IEEE 802.11 networks, the AP does not directly control either the channel access or the resource allocation. However, device-to-device communication has not been used in cellular networks. In cellular networks information is delivered to the destination user equipment (UE) through base stations. The base station generally controls channel access and allocates resources even when the communication is between UEs in the same cell.

Incorporating D2D communication as a possibility in cellular communication can improve the efficiency of cellular networks. When the UEs are close to each other compared to the distance to the base station, D2D communication is more energy and bandwidth efficient than communications through a base station. Figure 2 illustrates a case which the D2D communication is more efficient.Because the channel access and resources are controlled by the base station, the D2D communication in cellular networks should also be controlled by the base station. Thus, the base station grants approval for D2D communication between local UEs in the same cell only if it is more efficient than the legacy communication through the base station. Communication using D2D is appropriate for UE nodes in close proximity. When the distance between UE nodes increases, D2D communication throughput degrades drastically [1]. Because of the proximity, D2D communication requires less resources than the normal cellular communication, which leads to the improved total cell capacity [2]. A coordinated resource allocation for D2D communication to manage the interference has been proposed [3].

We model D2D communication as a form of wireless communications that supports proximity based application services. One example appropriate for full duplex D2D communications is when mobile users want to play a popular game with another mobile user in the area. File, image, or video sharing between users in proximity is another example appropriate for D2D communication. As more social service or proximity based service become available through mobile devices, there will be more need for D2D communications.

Full duplex communication is typically implemented using either frequency division multiplexing or time division multiplexing. In order for D2D communications to take place it is necessary that radios are capable transmitting and receiving on a single frequency. However, strong self interference at the receive antenna from the simultaneous transmission at the transmit antenna presents a challenge in implementation. A combination of analog and digital interference cancellation can suppress the self interference [4] and [5]. A full duplex radio with two antennas has been implemented and shown to achieve better performance than the half duplex 2x2 MIMO communication at low transmit power levels [5]. In [6] and [7], MAC protocols using full duplex communication were proposed in the context of an ad-hoc network. The adoption

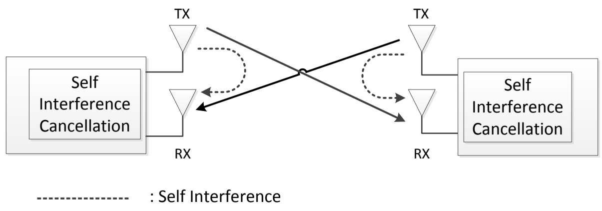

Fig. 1. Full duplex communication system

of full duplex communication for cellular communication was considered in [8] for infrastructure based communication.

The characteristic of full duplex communication matches well with D2D communication. The D2D communication is used in a close distance and full duplex communication performs better in shorter distances. At shorter distance, the self interference of full duplex communication decreases due to the lower transmit power. In this paper, we propose a full duplex D2D communication protocol in cellular networks. We also analyze the bandwidth efficiency of single frequency D2D communication protocol and compare it with legacy cellular communication schemes. We show that the single frequency D2D communication improves the cell bandwidth efficiency.

The outline of this paper is as follows. In Section II, we introduce the system model. In Section III, we analyze the performance of single frequency D2D communication. In Section IV, we propose the resource allocation protocol for single frequency communication and analyze the performance. Conclusions are given in Section V.

II. System model

We assume that the same overall frequency band is shared for both D2D communication and for primary (mobile-to-base and base-to-mobile) cellular communication. We assume the network operates with a total 10MHz band and is based on the orthogonal frequency division multiple access (OFDMA).

A. Channel model

We assume independent and identically distributed (iid) Rayleigh fading for different portions of the bandwidth (and during different time intervals). In addition, there is a distance dependent path loss. When the transmitted signal power on a particular frequency is P_t, the received signal power at a distance d_1 is

$$P_r = |h|^2 \frac{P_t}{d_1^\alpha}. \tag{1}$$

where h is the Rayleigh fading and $E[|h|^2] = 1$ and α is the path loss exponent. When MIMO is used, the channel fading on a particular frequency h is replaced with the fading matrix H between antenna elements at the transmitter and receiver. The bandwidth available for either type of communications is sufficiently large relative to the coherence bandwidth so that the fading is independent from one.

B. Radio model

We assume that the radios are equipped with two antennas. In the D2D mode of transmission one antenna is used for transmission and the other antenna is used for reception.

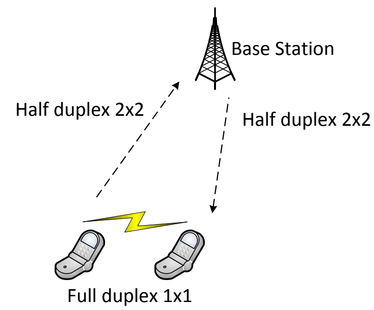

Fig. 2. Comparison of full duplex D2D and infrastructure communication

We consider the case whereby a user can transmit on one antenna while simultaneously receiving on the second antenna as shown in Figure 1. However, the transmitted signal from the transmit antenna of a node interferes with the received signal at the receive antenna at the same node. Both analog and digital interference cancellation are used to partially cancel the self interference. However, it is not possible to cancel the self interference perfectly. When a node is transmitting power P_t, the amount of residual self interference power KP_t where K is the self interference cancellation factor. As the transmitted signal power increases, the residual self interference increases. When the channel between two users is an iid fast fading channel with a distance dependent path loss, the SINR of full duplex communication can be expressed as

$$SINR = \frac{P_t/d_2^\alpha}{N_0 W + KP_t} \tag{2}$$

where P_t is the transmit power level for D2D communications and d_2 is the distance between the two nodes.

C. D2D communication model

We assume that D2D communication is used only between the UEs in the same cell because the resources for D2D communication should be controlled by the base station and devices in different cells may not be able to directly communicate or else would be inefficient. The bandwidth allocation for D2D communication will be described in next chapter.

To establish D2D communication, two steps of preparation are required. The first step is discovery. Discovery is a procedure to find available services in proximity area. When an application in a user's mobile device is to be supported by D2D communication, the possibility for D2D communication should be determined. User devices need to be able to determine whether the other device is in proximity in the same cell and also capable of D2D communications. There are service discovery protocols such as Flashlinq [9] and Wi-Fi Direct [10]. Flashlinq is designed to support service discovery in cellular networks. The second step is the D2D communication setup. The UEs request D2D communication to the base station and the base station determines which of the two communication schemes (D2D and normal) is more efficient. When D2D communication is determined to be more efficient than communication through the base station, D2D communication is allowed and the resources are allocated. In this paper we assume the first step is successful and only consider the second step and actual D2D communication. We assume that the channel state such as path loss and fading between the UEs for D2D communication is known to the users through the discovery procedure. In protocols such as Flashlinq [9], a special type of beacon is used to broadcast or discover service and UEs estimate the channel to other user devices by hearing the beacon.

Because full duplex communication can transmit and receive on the same frequency band, it can improve the bandwidth efficiency of a cell. When D2D communication is used for communication between two UEs in the same cell, it uses half bandwidth compared to infrastructure based communication (FDD). Figure 2 illustrates the difference between the full duplex D2D communication and infrastructure based communication. When a user device communicates with the base station, it uses both antennas in half duplex mode.When a user device adopt D2D communication, it utilizes full duplex communication which uses 1 antenna for each direction.

D. Infrastructure based communication model

We assume that the frequency division duplexing based cellular communication is used in cellular networks. There can be two cases for the infrastructure based communication. The first case is the communication between the UEs in the same cell. In our protocol, UE requests D2D communication when it needs to communicate with another UE in the same cell. When the base station determines that the legacy cellular communication is more efficient than D2D communication, two UEs communicate through the base station. In this case, double frequency bands are needed for communication. Each frequency band is allocated to each UE for communications with the base station. For the communication between a UE and the base station, FDD is used. We assume half of the allocated bandwidth is used for uplink and the other half is used for downlink. The bandwidth allocation for D2D communication is described in the next chapter. The second case is an UE connects to an entity outside the cell. The entity can be either a server on the internet or another UE in another cell. For both cases, we only consider the overhead between a UE and the base station. The communication of the second case cannot be replaced by D2D communication and is the same with legacy cellular communication.

For the comparison with D2D communication, we consider the bandwidth efficiency of infrastructure based communication. We assume that 2x2 MIMO communication is used and the communication achieves the 2x2 MIMO channel capacity with the channel state information at the receiver. Then the capacity is [11]

$$C = E_H \left[\log \det \left(I_{2\times 2} + \frac{1}{N} \frac{HH^*}{2} \right) \right] \tag{3}$$

where N is the noise variance and H is the channel matrix for 2×2 MIMO communication. In practical cellular communications systems, there is overhead transmissions such as control or signaling information that needs to be exchanged between

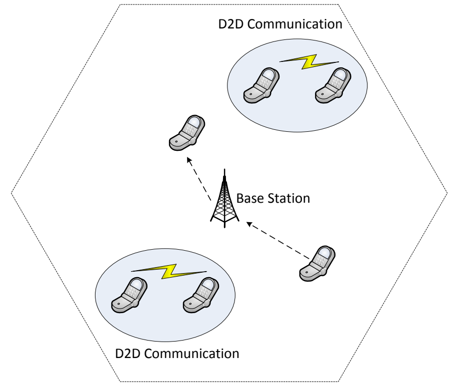

Fig. 3. Full duplex communication system

the user and the base station. However, in this paper we only consider the actual packet transmission because the amount of overhead needed for both D2D communication and cellular communication are comparable.

III. Full duplex D2D communication protocol

A. D2D communication setup

In this section, we describe the D2D communication setup protocol. A UE requests D2D communication with another UE via the base station and include the D2D channel state information in the request. When D2D communication is more efficient than cellular communication, the base station assigns a frequency band for D2D communication. Figure 3 illustrates a cell with D2D communication functionality. We assume the channel state between UEs and the base station is known to the base station by the reference signals in cellular communication [12]. When the base station finds that the infrastructure communication is more efficient than the proposed D2D communication, it allocates resources for the communication through the base station. When D2D communication is completed, the devices inform the base station of such in order to reallocate the resource.

B. Criteria for D2D communication

With the given channel state information, the base station determines whether the D2D communication is more efficient than the communication through the base station. Let h_{D2D}, be the 1x1 channel state for D2D communication. Let $H_{b,i}$ is the 2x2 channel state between user i and the base station. When two UEs have packets to transmit to each other consisting of M bits. We assume the channel reciprocity for D2D communication. Then the time consumption for two way packet transmission using full duplex D2D communication is

$$T_{D2D} = \frac{M}{WE[\log_2 (1 + |h_{D2D}|^2 SINR)]} \tag{4}$$

where $SINR$ is given in (2). The time consumption for the two way packet transmission in a cell using infrastructure based communication is

$$T_{inf} = \frac{M}{\frac{W}{2} E\left[\log_2 \det\left(I_{2x2} + \frac{2}{N_0 W}\frac{P_{inf}}{2d_1^\alpha} H_{b,1} H_{b,1}^*\right)\right]} + \frac{M}{\frac{W}{2} E\left[\log_2 \det\left(I_{2x2} + \frac{2}{N_0 W}\frac{P_{inf}}{2d_2^\alpha} H_{b,2} H_{b,2}^*\right)\right]} \quad (5)$$

where d_1 and d_2 are distances between each user device and the base station, and P_{inf} is the transmit signal power level for the infrastructure based communication.

Then the effective throughput for the full duplex D2D communication, S_{D2D}, and for the infrastructure based communication, S_{inf}, are

$$S_{D2D} = \frac{2M}{T_{D2D}} \quad (6)$$

and

$$S_{inf} = \frac{2M}{T_{inf}}. \quad (7)$$

When the base station receives D2D communication request and relevant information from UEs, it compares the effective throughput of two schemes, (6) and (7), and choose the transmission scheme that achieves higher throughput.

C. Resource allocation

The bandwidth for communication should be allocated by the base station. The communication between two UEs in the same cell requires two frequency bands because each UEs need to access the base station. D2D communication and cellular communication with entities outside the cell requires one frequency band. We define a unit bandwidth as

$$W_{unit} = \frac{W}{N_{D2D} + 2N_{Cin} + N_{Cout}} \quad (8)$$

where W is total bandwidth assigned to the cell, N_{D2D} and N_{Cin} are number of pairs that use D2D communication and cellular communication between UEs in the same cell, respectively, and N_{Cout} is the number of UEs that communicate with entities outside the cell. Then D2D pairs communication and UEs communicate with outside entity are assigned with one unit bandwidth, and cellular communication between UEs in the same cell is assigned with two unit bandwidth. Each unit bandwidth is allocated for each UE in that case.

IV. Performance analysis

As the first step of performance analysis, we compare the throughput of communication between 2 UEs in the same cell when they use full duplex communication and infrastructure based communication. We assume that two UEs are separated by 100m. The distance from each UE to the base station is assumed to be equal for both UEs and is varied from 100m to 900m. We also assume that infrastructure based communication use the 20dBm transmit power and D2D communication use 10dBm transmit power. The path loss exponent, α, is assumed to be four. We assume that 130dB self interference cancellation is achieved by the full radios. Figure 4 shows the throughput performance of full duplex

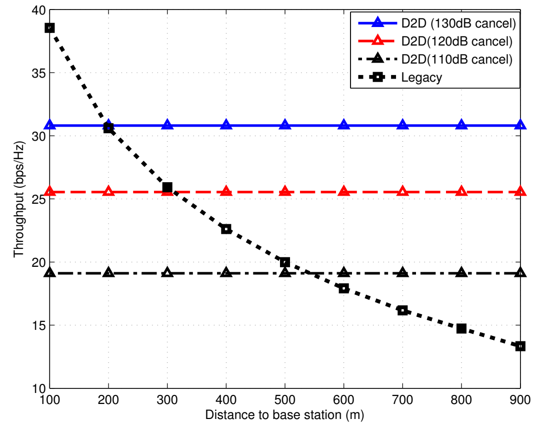

Fig. 4. Throughput comparison between D2D communication and infrastructure based communication

communication and infrastructure based communication. First, we can see that the self interference cancellation determines the throughput of full duplex communication. With less self interference cancellation, less throughput is achieved by full duplex communication. We can see that the D2D communication becomes more efficient than infrastructure based communication as the distance between UEs and the base station increases. As the distance from the base station increases, the throughput of infrastructure based communication degrades. However, the performance of D2D communication does not degrades with the distance to the base station. We comment that the performance of full duplex D2D communication improves when the distance between UEs decreases. At shorter distance, less transmit power is required and it decreases self interference, which improves the throughput. The performance of full duplex communication is sensitive to the amount of self interference cancellation. Currently self interference cancellation can reduce the self interference by 110dB [13]. We show result for 110dB, 120dB and 130dB interference reduction.

As the next step performance analysis, we consider the sum capacity of a cell when it supports full duplex D2D communication if it is more bandwidth efficient. We also compare the sum throughput performance with the case when only the infrastructure based communication is supported in the cell. The sum capacity is the sum of all effective throughput achieved in a cell at ont time. We assume that the cell shape is hexagon that fits into a 1km radius circle. We assume that there are 100 users in a cell. There are two types of users. The first type of users communicate with entities outside the cell. As the second type of user we assume $m\%$ of total users want to connect with another user in the same cell. They request D2D communication and allowed when full duplex D2D communication improves the throughput. When it is not allowed they communicate through the base station. We randomly place 100 UEs in a cell. We assume that UEs choose a D2D communication partner as the closest neighboring UE, which is done by the discovery algorithm. We assume that D2D communication use transmit power of 10dBm and cellular communication use 20dBm transmit power.

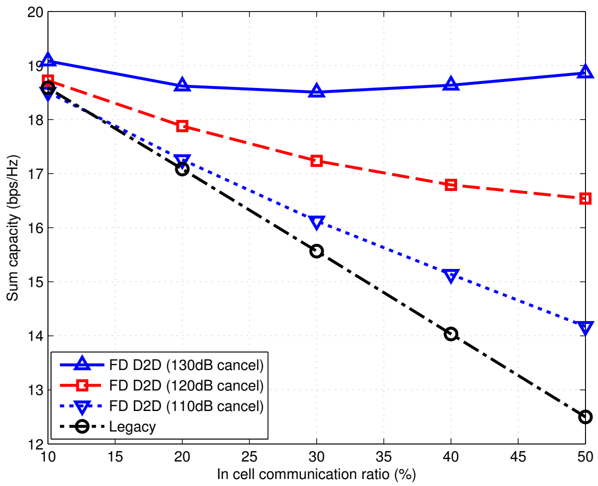

Fig. 5. Sum throughput comparison between full duplex D2D communication and legacy cellular communication

Figure 5 shows the sum capacity comparison between the full duplex D2D communication enabled cell and the legacy cell. First, we can see that the sum throughput of legacy cellular communication decreases as the in-cell communication ratio increases. Because in cell communication requires double bandwidth than other cases, an increase of in-cell communication degrades the bandwidth efficiency of a cell. Second, full duplex D2D communication can avoid the significant performance degrade. With full duplex D2D communication, a cell can support communication demand between UEs in the same cell with half resource compared to the legacy cellular communication. However, the full duplex D2D is allowed only when it is more efficient than infrastructure based communication. When the in cell communication ratio is low, the probability that even the closest neighbor UE is at a longer distance is high. In that case, infrastructure based communication can perform better and full duplex D2D communication is not allowed by the base station. As such, the sum capacity can decrease as the in cell communication ratio increases. As the in-cell communication demand increases, there is higher probability that UEs request D2D communication are close to each other. As a result, the sum throughput of 130dB self interference cancellation increases again as the in-cell communication increases more. Third, the sum capacity of a cell with full duplex D2D feature depends on the self interference cancellation amount. With less cancellation, full duplex D2D communication performs better than infrastructure based communication only when UEs are very close to each other. As such, the adoption of full duplex D2D decreases as the self interference cancellation decreases and it leads to the decrease of sum capacity. Nervertheless, the full duplex D2D communication improves a sum throughput larger than legacy cellular communication in all self interference assumption and the performance gain increases as the in-cell communication ratio increases. When the in-cell communication ratio is 50%, the full duplex D2D enabled cell achieved 13% (110dB cancel), 32% (120dB cancel), and 51% (130dB cancel) higher sum throughput than legacy cell.

V. Conclusion

In this paper, we investigated the performance improvement of full duplex D2D communication compared to infrastructure based cellular communication. D2D communication is an overlay communication scheme that allows users in proximity to exchange packets in a peer-to-peer manner. It can improve cell capacity when the users are close to each other. Single band full duplex communication which transmits and receives in the same frequency band matches well with the characteristic of D2D communication. It performs better than half duplex communication when the distance between two users are short. We proposed a protocol for the adoption of full duplex D2D communication in cellular networks. It is shown that the proposed protocol and full duplex D2D communication improves the cell capacity as well as the effective throughput between two users. It is also shown that as the ratio of in cell communication increases, the performance gain of full duplex D2D communication to the legacy cellular communication increases. We conclude that full duplex D2D communication can be a good candidate to improve the bandwidth efficiency of future cellular communication networks where many proximity based communication service need to be supported.

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