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A Short Review of Current Challenges and Potential Applications of Full Duplex in Wireless Networks

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Abstract

Recent advances in self-interference cancellation (SIC) techniques have made the implementation of Full Duplex (FD) possible.FD technology promises doubling the capacity of wireless networks without needing new frequencies, by enabling communication devices to receive and transmit at the same time and frequency. However, when considering the overall communication networks, gains may be less significant or even non-existent. The purpose of this article is therefore to identify the most promising applications of FD. Based on the study of the available literature, we establish that Device-to-Device (D2D) communication and femtocell deployments might be some of the best use cases to unlock the potential of FD communications.

1 Introduction

A fundamental limitation of wireless communications lies in the scarcity of the radio spectrum. Thus, any increase in capacity and data rate is limited by the lack of spectral resources. Full Duplex (FD) is a promising solution to overcome the need for additional spectrum. Even though the feasibility of FD has been demonstrated [1], only Half Duplex (HD) is currently used in wireless networks [2]. The promise of doubling channel capacity by having FD instead of HD communications is very attractive. Moreover, doubling capacity is not the only advantage brought by FD technology. It may also enable fast collision detection, secure transmissions, and reduce latency [3]. However, if the challenges faced by FD are not properly addressed, HD may end up having still a better channel capacity [4] and remain the most suitable solution.

The main drawback of FD communications lies in the additional interference it creates compared to traditional HD systems. Intracell interference, uplink-to-downlink and downlink-to-uplink inter-cell interference are the main ones that need to be mentioned. The most detrimental type of interference generated by FD is self-interference (SI). Indeed, the receiver collects data from another transmitter but it also receives its own data sent at the same time [3]. In [5], it is stated that SI might not decrease the overall throughput if its level is at least 3 dB under the noise level. Recently, new breakthroughs in SI cancellation (SIC) have recently made it possible to reach this level of cancellation and have therefore made the implementation of FD technology possible.

There are two kinds of SIC techniques as presented in [6]. On the one hand, one may take advantage of passive SIC, which is offered by the path loss between the transmitter and the receiver of the same device. Two solutions can be implemented. The first one consists in increasing the physical separation of antennas to decrease the power of SI, a solution that may be impractical for certain applications, for example in cell phones [7]. The second one relies on exploiting the lobes' characteristics of the antenna radiation patterns to ensure a minimum intersection between the transmit and receive ones [6]. On the other hand, some works have proposed active SIC techniques which can be performed in the analog or digital domain [6].

A combination of passive, analog and digital cancellation techniques is necessary to meet the signal-to-interference ratio (SIR) level required by FD. However, once it is achieved, challenges remain in terms of hardware realizations. Indeed, current medium access control (MAC) protocols for HD communications do not require as many identifiers (packet headers, packet duration, etc.) as FD [3]. Moreover, even if SIC techniques are now advanced enough to facilitate the hardware realization of FD, it cannot be implemented in all kinds of wireless networks. In this article, we will thus first explore in Section 2 in more details the difficulties and costs associated to implementing FD and question the legitimacy of FD in some applications, compared to HD. Then, in Section 3, we will list the different advantages FD has to offer. Based on this review, we will conclude in Section 4 by pointing out in which applications FD is most relevant.

2 Challenges for applications of FD in wireless networks

FD presents several crucial challenges that condition its adoption in future communication networks, namely: (i) increase in the overall amount of interference, (ii) need for a fully efficient MAC protocol design and (iii) necessity to keep power consumption to the required standards of mobile communications. As we present these challenges, we will show that some of these issues are still to be resolved before FD can be fully implemented at different levels in wireless networks. In some cases, we will see that the trade-off between the increased complexity and the gain in spectral efficiency is not interesting enough to replace HD. In other cases, technology is not ready enough yet to support FD as the resulting Quality of Service (QoS) would be too deteriorated compared to HD.

2.1 Interference increase

In Fig. 1, we show that, compared to a traditional HD environment which would be based on time division duplex (TDD) or frequency division duplex (FDD), the introduction of FD at the base station (BS) level would create new types of interference in cellular networks. As stated by Goyal et al. in [2], FD would add user equipment (UE)-to-UE interference, BS-to-BS interference as well as SI within the BSs. The first can be reduced with the technological advances in cancellation techniques [7]. However, because of the strength of power transmission of BSs, the last two kinds of interference are much more complicated to reduce. Indeed, BS-to-BS interference would be very strong as the path loss between two BSs which are frequently placed at higher elevations may be low [2]. Moreover, due to the high transmit power, the fairly weak uplink signal of BS 1 would be greatly affected by the powerful downlink signal from BS 2, hence the importance of downlink to uplink interference between BSs as pointed out in [3]. Finally, authors in [2] point out through a numerical comparison of signal strengths and SI that -20 dB is the maximum SIR that could be reached in a 1 km radius cell, thus concluding that cancellation circuit technologies are currently not performant enough to ensure a practical deployment of FD radios in large cells. Therefore, a scenario in which FD would be deployed in large cells at both UE and BS level seems today to be out of reach. Furthermore, even if there was a breakthrough in cancellation techniques in the near future, these would still come at a high cost in terms of power consumption, as we will later detail.

2.2 MAC design

A FD system offers the potential to achieve simultaneous sensing and transmission, which is particularly appealing for application in Cognitive Radio (CR) networks. Indeed, with HD, Secondary Users (SUs) sense the channel before transmission, using the Listen-Before-Talk (LBT) protocol and therefore sacrifice transmission time for spectrum sensing. Using a novel protocol called Listen-And-Talk (LAT) as proposed in [8], time utilization could be optimized with FD system. However, with this type of protocol, new issues appear at the MAC layer, such as evaluating and optimizing sensing performances as well as managing the access to the spectrum among all users.

First of all, the LAT protocol and some other sensing schemes use energy detection in order to determine whether the spectrum is free or not. However, the precision of this sensing technique is directly linked to the interference level, particularly that of SI, as it can greatly affect the measurements. Hence, improving spectrum sensing relies closely on developing better SIC techniques.

Looking at the different metrics used for evaluating sensing performances, the two main metrics appear to be spectrum waste ratio and collision ratio [8]. The first one is determined by the ratio where the spectrum is not fully used with no user, primary or secondary, transmitting. The collision ratio is the most important one as it measures the ratio where two users both transmit at the same time and a collision happens. In order to address these collision problems and optimize the two metrics, diverse scenarios for spectrum access are addressed in [8].

First, distributed dynamic spectrum access is presented as a potential solution to avoid the complexity of deploying a central controller allowing SUs to access channels that are usually allocated to primary users (PUs). However, this scenario has two main problems: SUs can collide without detection of the collision and most of all, transmission does not cease in the case of a collision, which leads to a very high collision ratio.

On the opposite, centralized scenarios, where a FD access point or a FD relay system are deployed, have also been explored [8]. These seem much more achievable since it would not require SUs to do the spectrum sensing. Instead, the problem would be focused on the central FD point, which would thus lower the complexity required for spectrum sensing in SUs. Indeed, algorithms for spectrum sensing would also be a cause for power consumption in SUs. Therefore, the central FD access point or relay would manage the access to spectrum for all SUs connected to it, acting almost as a secondary BS. As seen throughout this article, the main remaining issue would lie in resolving SI at this FD point in order to reach acceptable levels of QoS.

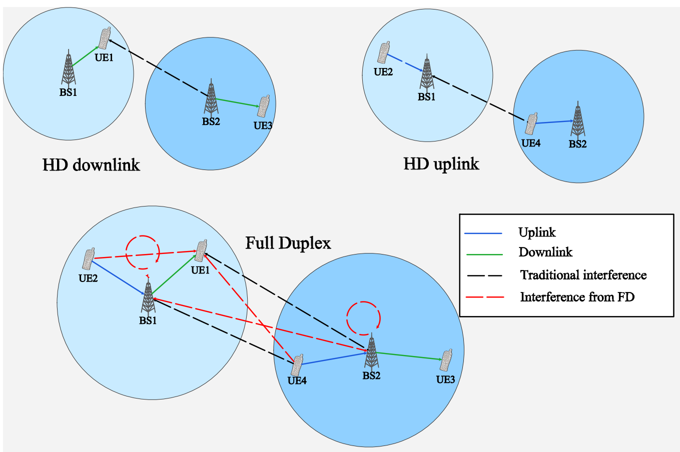

Figure 1. HD and FD multi-cell scenarios (from [2])

2.3 Increase in power consumption

As aforementioned, the increase in complexity brought by the new required SIC techniques and MAC algorithms would induce an increase in the power consumption of wireless devices. Hence, the implementation of FD would not be entirely beneficial as it would increase power consumption of every component of the network. This would be especially detrimental for mobile UEs. Therefore, the greatest challenge lies in keeping the power consumption of the latter within acceptable levels.

The diversity and complexity of the services and applications supported by smart phones have considerably reduced the autonomy of their batteries, down to a point where users are most frequently forced to recharge them once a day. It seems unlikely to picture users accepting to have their smart phones' autonomy greatly reduced in order to achieve gains which, at their level, would not be significant. Indeed, despite the fact that the gap between uplink and downlink traffic tends to decrease, asymmetric traffic reduces the need for simultaneous uplink and downlink transmissions [2]. This imbalance limits the benefits of FD communications. It appears that the needs for a bidirectional bandwidth seem to be overestimated. Even with online storage services, traffic demand is half-way most of the time. Finally, increasing power consumption at the BS would be more acceptable but it goes against the current trend of improving the energy efficiency of communication networks [9].

3 Advantages and applications of FD

Based on the different aforementioned challenges, in this section we go through some promising applications of FD.

3.1 FD for BS QoS enhancement

We have seen in section 2 that FD inter-cell communications between BSs are not feasible due to very strong SI. Nevertheless, it would still be interesting to implement FD capability within a cell. BSs are the primary node for current major networks. Because they are mostly owned by operators, investments are easier to manage than for UEs. Currently, BSs are based on either TDD or FDD modes. FDD implies that uplink and downlink signals are transmitted on different frequencies, and therefore propagate through a different wireless environment. With FD, as the same channel is used for the two transmissions, fading characteristics will be the same. Therefore, it will be easier for the BS to correct the signal thanks to the analysis of its received signal, on the same frequency. For TDD, the propagation characteristics are known as there is only one frequency used, but FD would enable the BS to correct the outgoing signal in real-time, while there is a delay in the correction in TDD. Therefore, FD would enable superior performances at the BS.

3.2 FD for femtocells

Femtocells are interesting for improving spectral and energy efficiency, while offloading traffic from macrocell BSs [10]. Compared to a macrocell whose cell radius is considered to be around 1 km wide, a femtocell is about 40m wide in a typical isolated indoor environment [2]. As a consequence, in a femtocell, users transmit at a much lower power than a macro BS. As presented in Section 2, FD capabilities and efficiency highly depend on SIC and SIR. Reducing transmit power is a direct way to reduce SI [10]. Therefore, FD is likely to be applicable in femtocells. Indeed, we can estimate the ratio between transmit and received signal in a 40m radius cell being about 77dB. As presented in [1] in which Bharadia et al. present a single-antenna design with up to 110dB of cancellation, a SIR as high as 33 dB could be obtained in such a femtocell. This shows that FD is indeed applicable in femtocell deployments. Implementing FD could reduce the needed bandwidth while maintaining the QoS, and therefore allow twice as many UEs to use the same femtocell. Therefore, FD could also be used to raise the number of UEs connected to a femtocell.

To reduce interference between cellular terminals attached to the macro BS and femtocell users, the latter may implement spectrum sensing. In such a network, macrocell users would be considered as PU, while femtocell users would be SU. As the femtocells are based on random deployments, the main task of the femtocell is to sense the spectrum environment, and to allocate channels that are not occupied by the macrocell to the femtocell users, without disturbing PUs. Thus, applying CR techniques to femtocell deployments enables lower cross-tier interference by listening to PUs and adjusting the transmission of SUs accordingly. As presented in section 2.2, FD in femtocell could increase listening performance by allowing to sense the spectrum while using it. Hence, with FD, real time adaptation becomes possible to ensure minimum interference to the macrocell.

3.3 Implications of FD for UEs and D2D

When UEs are in close proximity, they may communicate directly by forming a D2D link, without a third party being involved, and offload traffic from macro cells. The short distance between UEs enables low-power emissions for both devices and thus lowers their energy consumption. For battery-powered UEs, this results in autonomy gain. Similarly to the case of femtocells, with a lower transmit power, SIC will be more efficient. Therefore, FD seems well adapted for D2D transmission.

Moreover, to enable D2D connections, UEs need to detect each other. Most methods used for peer discovery consist in listening for beacons from others devices, while sending some other beacons in return. With HD methods, the discovery time could be long, because the equipment cannot receive beacons while transmitting. In [11], it is shown that

FD could be used to reduce discovery time in D2D-enabled networks. This is an additional reason that shows the suitability of FD for D2D communications.

Moreover, SIC is based on 3 different cancellations techniques, the most important being passive suppression. In order to achieve sufficient passive suppression, upgrading UEs' hardware will be necessary. The production cost of FD antennas is as of today a great concern. With a high production cost and a higher power usage, FD-compatible UEs aren't ready for the consumer market yet. Nevertheless, the manufacturing cost could easily be reduced with mass production if FD transceivers were to massively equip consumer products. Therefore, if D2D deployment is met with commercial success by enabling killer applications we don't even imagine today, it may well motivate a mass production of FD devices that would definitely trivialize the FD technology.

4 Conclusion

Based on the review presented in this paper, we can conclude that, with the currently available SIC techniques, FD is difficultly applicable in network deployments which require users to transmit with high power. Besides, we pointed out that it is not well adapted for applications where traffic is not symmetric. Therefore, we can conclude that FD will first reach its full potential for short distance communications between equivalent users. Examples of such deployments include femtocells and D2D communications, two use cases to be soon introduced in 5G networks and which may well be catalyzed by FD.

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