Robust Interference Management and Network Design for Heterogeneous Full-duplex Communication Networks

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1 Introduction

The arrival of 5G New Radio Release-15 introduces a new service class, namely ultra-reliable low latency communication (URLLC), alongside enhanced mobile broadband (eMBB) services. A wide range of design requirements in terms of the data rate, latency, reliability and energy efficiency are targeted by 5G new radio (NR). Novel technology components are needed to meet such challenging requirements. For example, full-duplex (FD) communication, i.e., simultaneous transmission and reception over the same frequency band, opens the door to significant improvements in terms of throughput, reliability and latency as well as secrecy rate [1, 2], provided the challenges associated with FD transmissions are well managed. It has been demonstrated that FD capabilities result in significant aggregate throughput gains [3] and latency reductions [4] over baseline half-duplex (HD) scenario in ideal conditions.

There are two major challenges in realizing the potential of FD communication in practice. The first relates to FD node design itself, while the other involves interference and traffic management. FD communication generates strong loopback interference from the transmitter to the receiver-end of the same radio device, which can be in the order of 100 – 120 dB higher than the noise floor. Though recent advances in self-interference cancellation (SIC) techniques, featuring a combination of

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active (analog and digital) and passive cancellation allow suppressing the loopback interference to tolerable limits, self-interference cannot be completely eradicated [1]. From the network perspective, FD communication doubles the number of concurrent transmissions, resulting in an increase in the overall network interference. Furthermore, the opportunities arising from simultaneous uplink and downlink transmission can only exploited when packets are readily available for transmission in both directions. Hence, the envisioned performance gains cannot be fully realized without addressing such practical aspects of FD communication.

This chapter focuses on the network aspects of FD communication. We first evaluate the potential performance gains of FD communication through system level simulations under a practical network scenario. The dense small cell scenario is specifically assumed since densification is identified as one of the main tools in meeting the ambitious 5G design targets [5]. Instead of the generic full buffer traffic model, realistic traffic protocols like the Transmission Control Protocol (TCP) and the User Datagram Protocol (UDP) with variable traffic profiles, and physical/medium access control (PHY/MAC) layer techniques like hybrid automatic repeat request (HARQ) retransmissions and link adaptations are considered. The considered degree of realism in our assumptions allow us to get insights into the potential performance gains of FD communication in dense small cell networks under realistic network conditions.

We then present techniques to improve the performance of FD communication through efficient intra and inter-cell interference management and FD-aware network design. In particular, we propose the virtual FD technique, which is a way to mimic FD transmission using HD transceivers, thereby avoiding the need for SIC and the detrimental impact of residual self-interference power. Our results demonstrate that simultaneous scheduling of uplink and downlink users in two neighbouring cells through cooperation between the access points (APs) can outperform FD transmission and results in improved reception. More specifically, up to 70% success probability gains over conventional FD communication can be observed with the proposed interference management technique.

In addition to its role in throughput enhancement and latency reduction, FD communication - by its nature - lends itself to applications in other domains, such as spectrum sensing, physical layer security and device-to-device (D2D) communication. As a final contribution, we discuss how FD communication can provide gains in relaying, self-backhauling, autonomous D2D discovery and physical layer security.

2 Full-Duplex Network Design: Challenges and Performance Trends

A major appeals of FD technology is the possibility of boosting the network throughput. This is particularly attractive when operating in the centimeter-wave spectrum region, given the scarcity of available frequency resources. A further less intuitive benefit is latency reduction for services running over unpaired bands, where

Time Division Duplexing (TDD) is the traditional operational mode. The possibility of simultaneously transmitting and receiving removes delays associated to uplink/downlink ratios of the TDD frames. This has significant potential in scenarios where a transmitter needs to sense the channel, for example, in Carrier sense multiple access (CSMA), D2D discovery applications, and cognitive radios.

2.1 Challenges in Full-Duplex Network Design

The second major challenge of FD communication is in the networking aspect. Simultaneous transmission and reception enabled by FD leads to an increase in the interference footprint with respect to traditional duplexing. While traditional network deployments are affected by a single direction interference at a given time/frequency slot, base stations (BS) and devices can experience interference from both uplink and downlink transmissions in neighbor cells with FD communication, as illustrated in Figure 1. This is particularly significant in dense deployments (e.g., dense small cells), given the short intersite distance and the similar power level in uplink and downlink directions. In the case of large cells with significant uplink/downlink power asymmetry, the downlink interference is predominant and performance is deemed to be similar to that of half-duplex (HD) with uncoordinated uplink/downlink switching point between neighbor cells [6].

Two different FD modes are usually considered in the literature, namely base station full-duplex (BS-FD) and in-band bidirectional full-duplex (IB-FD). In the former case, only the BS is FD capable, while the terminals operate in traditional HD mode. In such a case, FD communication benefits from the ability to schedule uplink and downlink users simultaneously, at the expense of additional intra-cell interference at the downlink receiver. On the other hand, IB-FD assumes that both BS and user terminals are FD capable. The number of concurrent transmissions for both modes is doubled in comparison with HD operation, resulting in a substantial increase in the overall inter-cell interference (ICI). In particular, mutual coupling between cells specific to the network deployment obviously has a major impact on the FD potential due to such increased ICI.

The traffic flow density in the uplink and the downlink directions also impacts the expected performance enhancement of FD communication. More precisely, in order to benefit from the opportunity to schedule uplink and downlink traffic simultaneously, there should be available traffic in both directions, i.e., uplink and downlink traffic profile should be symmetric. However, network traffic is generally skewed in favour of either transmit directions (e.g., content uploading, video streaming). Even when the residual self-interference power and the increased intra- and inter-cell interference with FD communication are efficiently managed, the full potential of FD communication can only be availed in scenarios with symmetric traffic profiles, as pictorially depicted in Figure 1.

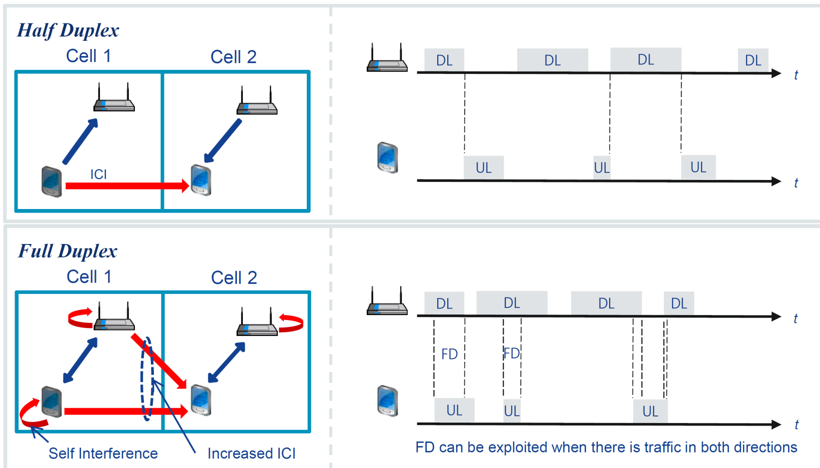


Fig. 1: Full-duplex communication results in increased inter-cell interference, incurs residual self-interference and is fully exploited with symmetric full buffer traffic in both directions.

2.2 Performance Evaluation of Full-Duplex Communication under Realistic Network Assumptions

We have highlighted how increased ICI may present a significant challenge for harvesting the potential gain of FD. In this section we evaluate the performance of FD transmission in a dense network of small cells characterized by tight interference coupling. The objective is to observe FD performance under realistic dense small cell scenario. The presented results are extracted from an event-driven system level simulator. We consider a single floor scenario with 20 small cells of 10 m $\times$ 10 m dimension arranged in a 10×2 formulation, as specifed by 3GPP. Each cell contains a number of user terminals and a single access point placed randomly, both transmitting at a 10 dBm power. The same frame structure is assumed for both link directions. Rayleigh fading model is assumed, while the path loss is given by the Winner II indoor office model.

As a further tier of robustness to the interference, we also consider an HARQ mechanism to be in place. It has been identified in [4] that FD has an attractive interaction with high layer protocols such as TCP, given the nature of its congestion control mechanism. In the initial stage of a service, the TCP congestion window which defines the amount of data to be sent through the channel, grows exponentially with the reception of TCP acknowledgements (ACK). When a certain threshold is reached, a contention avoidance phase starts, where the congestion window grows linearly. The congestion window might grow faster and reach the Congestion Avoidance phase sooner with FD transmission, allowing a larger amount of data transmission within a single transmission slot. The TCP implementation is New Reno, and includes the recovery and congestion control mechanisms. However, handshake procedures are not considered since they are not relevant for our studies.

In order to support FD communication, a radio resource management (RRM) module design that dynamically schedules the transmission between FD and HD mode at each TTI is considered. The scheduling decision at the AP and the UE is taken independently based on the information received from the PHY, MAC and radio link control (RLC) layers. Thereafter, links with scheduled traffic in both directions are allocated to FD mode. We refer to [4] for further details on the simulation setup.

2.2.1 Analysis of the Traffic Constraint Limitation in Isolated Cell

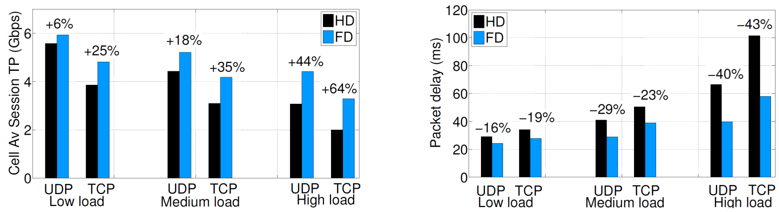
In order to first characterize the benefits of FD communication in interference free scenarios, let us consider for the moment an isolated cell in the aforementioned setup. Figure 2 presents the system performance (in terms of average cell session throughput and average packet delay) with UDP and TCP protocols, assuming a bidirectional FD setup with symmetric and asymmetric traffic profiles respectively. Low, medium and high loads correspondingly refer to resource usage of 25%, 50% and 75%.

For the symmetric scenario, a larger gain with FD communication is observed with TCP traffic. The reasons are twofold: firstly, the TCP congestion window grows faster with FD traffic, allowing larger amount of data transfer compared to HD communication. Secondly, the accumulation of traffic in the buffer in the slow start phase of the TCP congestion window build-up allows for better exploitation of the FD capability compared to UDP traffic, especially in low traffic load scenarios where the FD gain is 25% when TCP is used with respect to the 6% gain of UDP. FD further allows faster transmission of ACKs, which also contributes to the performance gains.

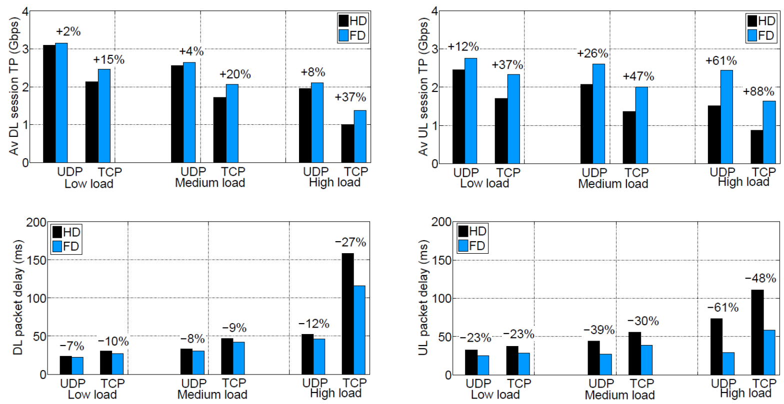
A traffic ratio of 6 : 1 in favour of downlink traffic is assumed for the asymmetric scenario. The gains are expectedly different for the different transmission directions. In general FD communication benefits the lightly loaded direction more. It is important to note that even though we consider an isolated cell (hence no ICI) and ideal SIC, the performance gains with FD communication are below the theoretical levels reported in [3] as a result of considering practical TCP/UDP traffic protocols.

2.2.2 FD Performance Under the Impact of Increased Interference and Traffic Constraints

We next investigate the impact of increased ICI. The results are presented in Table 1. A 5 dB wall loss is assumed. Only the medium load scenario and symmetric traffic is considered for the sake of brevity. The throughput performance (in Mbps) of HD, bidirectional FD and BS FD with symmetric TCP and UDP traffic in a multi-cell scenario are shown.



(a) Symmetric traffic profile



(b) Asymmetric traffic profile (6 : 1)

Fig. 2: Throughput gain and delay reduction of bidirectional FD over HD with TCP and UDP traffic in a single cell scenario.

The average uplink and downlink performance are similar under the bidirectional FD case. In the case of UDP traffic, around 40% and 20% outage and median throughput gains are respectively observed; whereas TCP traffic demonstrates a huge outage throughput loss of over 70% and median throughput loss of over 60%. Due to the TCP slow start, FD is exploited much more often compared to UDP (in this case 81% TCP transmission were FD compared to 15% with UDP), resulting in increased ICI, which is further exacerbated in the dense small cell scenario. In addition, HARQ retransmissions are triggered more often with FD in TCP, further congesting the network.

In the BS-FD mode, similar trends are observed with both TCP and UDP traffic. The downlink direction is affected by the additional interference resulting from the concurrent uplink transmission, while the uplink direction slightly benefits from the increased transmission opportunity accorded by FD communication. Similar performance trends are observed for latency as well. Bidirectional FD results in lower latency with UDP protocol, whereas the delay increases dramatically with TCP. On the other hand, BS FD shows nearly the same results for UDP and TCP. This is because, exploitation in FD mode is limited due to the traffic constraints, which means that the gain that FD can bring on speeding up the congestion window in TCP is barely shown and therefore both schemes perform nearly the same.

	Downlink TP					Uplink TP				
	HD	BD FD	Gain	BS FD	Gain	HD	BD FD	Gain	BS FD	Gain
UDP Traffic Protocol										
Outage	1.1	1.6	45%	0.7	−36%	1.1	1.5	36%	0.7	−36%
Median	2.5	2.9	16%	2.4	−4%	2.5	3.0	20%	2.6	4%
Peak	4.6	5.1	11%	4.3	−6%	4.5	5.1	13%	4.8	7%
TCP Traffic Protocol										
Outage	0.4	0.1	−75%	0.3	−25%	0.4	0.1	−75%	0.4	0%
Median	1.3	0.5	−62%	1.2	−8%	1.2	0.4	−66%	1.3	8%
Peak	2.3	1.8	−22%	2.2	−4%	2.2	1.8	−18%	2.2	0%

Table 1: Throughput performance (in Mbps) of HD, bidirectional FD (BD FD) and BS FD with symmetric TCP and UDP traffic in a multi-cell scenario with 5 dB wall loss.

It is thus observed that the potential throughput and latency gains with FD communication are rather limited when practical considerations such as the impact of increased ICI and asymmetric traffic profile are accounted for.

3 Interference Management and Network Design for FD communication

The previous section highlighted the role of increased intra- and inter-cell interference and traffic asymmetry in limiting the potential of FD communication. Techniques to overcome these challenges and improve the performance of FD communication through efficient intra and inter-cell interference management and designing the network to have more symmetric traffic conditions are discussed in this section.

3.1 Interference Management Techniques in Full-Duplex Communication

The obvious benefit of FD communication are gains in terms of the throughput and latency. In the context of a cellular network where users are served by macro base stations with higher transmit powers, the throughput gains are higher in downlink [7]. However, the inter-mode interference limits the throughput gains that can be obtained in uplink, which can in fact be negative. In order to achieve its full potential, the FD node should be RRM-aware, and therefore, intelligently pair and schedule downlink and uplink users with proper transmission powers so as to reduce the intra- and inter-cell interference [8].

In [6], a smart scheduling between FD and HD mode, termed as $\alpha-$duplex is proposed to limit the adverse affect on the uplink interference. The authors propose to partially overlap between the uplink and the downlink frequency bands, so as to have FD operation in only the overlapped bands. The amount of the overlap is controlled via the design parameter α to balance the trade-off between the uplink and downlink performances.

For small cell networks with similar uplink and downlink transmit powers, the increased ICI equally impacts the performance gains in both directions. Limiting the interference coupling among cells is the best way to deal with the increased interference in this case. This can be done through physical isolation among cells, for example installing different cells in different rooms/apartments for indoor networks, or by using directional antennas. With BS-FD operation, where the different uplink and downlink users transmit simultaneously, taking the resulting uplink to downlink interference into account during scheduling decision can address the interference management problem to a large extent [9].

3.2 Inducing Traffic Symmetry Through Network Design

It has been shown in [10] that asymmetry in traffic profile between the uplink and downlink transmission directions impacts the achieved performance gains with FD. While this is not an impediment resulting from FD transmission itself, this fact has to be carefully considered in order to fully utilize FD networks. In this respect, FD communication has the highest potential in scenarios with symmetric traffic, such as relaying and backhaul networks and D2D communication.

FD relaying is perhaps the most successful application of FD communication, and one reason is due to the inherent availability of symmetric traffic. In a cellular deployment, for instance, a FD small cell can act as a relay for macro cell edge users. In cellular networks, the backhaul, which is composed of front, mid and back haul links, is the network that connects the small cell and macro BS to the core network. A practical low complexity backhaul solution is to leverage the radio access network spectrum simultaneously for the access link as well as the backhaul link, with advantages in terms of easy installation, reduced costs and flexibility. Due to the limited spectrum availability, FD transmission is recently being considered as a viable option for self-backhauling since it accommodates efficient reuse of the scarce access spectrum, with limited additional hardware cost [11]. Furthermore, the backhaul link can be designed such that the interference generated to the users operating in the network is limited, which can be achieved by allowing RRM coordination between the small cell and the macro BS [8]. With coordinated RRM between BS and relay, employing low cost FD relays for in-band backhauling is found to provide large gains over an equivalent HD baseline [8].

D2D communication is known to provide benefits such as network offloading, potential coverage extension, and reduction of control overhead and latency. In order to establish direct communication with potential neighbors, a discovery phase is required at each device. A typical autonomous discovery procedure consists of broadcasting of discovery messages (often referred as beacons) by each node. Upon awareness of the neighbours' presence, an eventually dedicated communication phase can start. The discovery procedure needs to be repeated with a certain occurrence in order to track new appearing nodes in the network. FD communication has significant potential in terms of latency reduction in the device discovery phase since every device can receive the beacons from its neighbors while simultaneously transmitting its own beacons [12]. On the other hand, since D2D communication are between two (usually) physically proximate and isolated users, the increase in intra- and inter-cell interference due to simultaneous transmissions, as discussed earlier, is rather limited.

4 Virtual Full-Duplex

The main challenge to the realization of the use of FD wireless transceivers is the high implementation complexity of transceivers that is required to cope with the induced self-interference. This is particularly one of the main motivations behind the BS-FD setup described earlier, where only the BS has to cope with the complexity of SIC while the user terminals operates in HD mode.

To resolve the self-interference issue in FD implementation, the use of interconnected HD macro-cell base stations is recently proposed [13, 14]. A distributed implementation of the FD functionality is realized by simultaneously serving users that have opposite uplink and downlink connections each. The interconnection between coordinating BSs is assumed to have sufficient capacity. The connected BSs form a *virtual* FD BS. Thus, the complexity of SIC and the impact of residual self-interference power [1] are readily avoided. The main benefit of virtual FD comes from shorter transmission distance between UEs and their serving APs.

The virtual FD concept can be extended to the small cell scenario as well. Virtual FD using small-cell APs can be realized by several different interconnection architectures. As in previous works, two APs can be connected directly. Alternately, two or more APs can be connected by a central unit similar to the Cloud-Radio Access Network (C-RAN) architecture. Due to the low mobility of users in small cell scenario, we can assume that the channel state information (CSI) can be perfectly shared among the connected APs.

In Fig. 3, signals are depicted as solid arrows, interference as red arrows, and the abstracted interconnection between nodes as a bold line. On Fig. 3 HD-AP2 sends the signal in the downlink to UE2, while HD-AP1 receives signal from UE1 in the uplink. HD-AP1 receives interference from HD-AP2, while UE2 receives interference from UE1. However, HD-AP2 can use the high-bandwidth interconnection to HD-AP1 to send the same data contained in the packet to UE2, such that HD-AP1 can regenerate the interference signal exploiting the received data and the available CSI, and cancel the interference from HD-AP2 perfectly. On the other hand, the signal from UE1 remains as interference to UE2. It can therefore be concluded that the setting on Fig. 3 operates equivalently with the setting containing a single FD AP. By utilizing TDD, the traffic directions of UE1 and UE2 are reversed in the next time slot, rendering it possible two-way communication possible for both UEs.

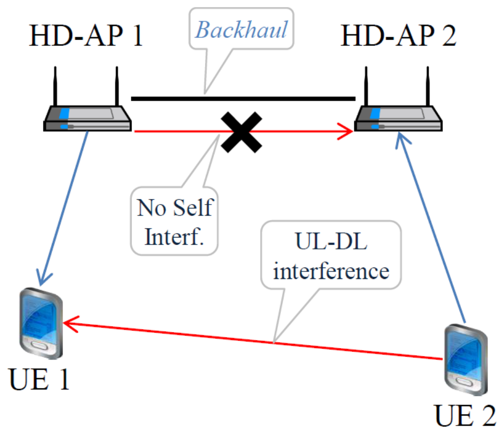


Fig. 3: Virtual full-duplex topology with two interconnected half-duplex access points.

In Fig. 4, the transmission success probabilities of virtual FD and FD are depicted. The curves are drawn by Monte Carlo simulation to model a 150×150 meters two-dimensional area. All small cell APs are randomly deployed and each UE is associated with its nearest AP. It is assumed that the transmission is successful when the received signal-to-interference-and-noise ratio (SINR) is above the target threshold. The transmission power of UEs and APs are the same at 10 dBm. The distance between virtual FD pair is less than or equal to 10 meters, a restriction added to model a dense small-cell environment. In the FD scenario, the APs are deployed according to a Poisson Point Process with half the density of virtual FD. This is because two HD-APs in virtual FD form a single virtual AP. In each cell, two UEs (one in UL, the other in DL) are served simultaneously resulting in the same number of UEs for the FD and the virtual FD scenarios.

We observe that the success probability of virtual FD is superior than FD over the entire target SINR range, with gains of up to 70%. This is because that UEs are located closer to the serving APs than FD. The above simulation assumes an ideal connection between cooperating APs. Because the two distant APs must exchange information in real time, the performance of the link connecting the two APs is important. In the case of a high density network, wired connection between these base stations may be more challenging. In this case, a wireless connection using millimeter wave (mmW) technology can be considered.

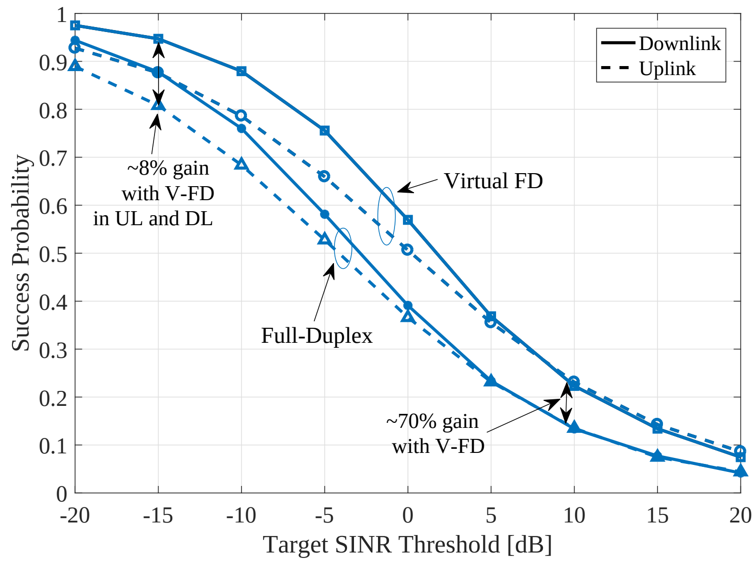


Fig. 4: Transmission success probability as a function of target SINR threshold.

5 Other applications of Full-Duplex

The role of FD communication in enhancing the throughput and/or latency has so far been highlighted in this contribution. In this remaining section, we present other application areas where FD communication has demonstrated the potential to provide significant performance gains.

5.1 Physical layer security

In the last few years wireless networks have become ubiquitous and an indispensable part of our daily life due to a broad range of applications. As a result, devices are even more vulnerable to security attacks, such as eavesdropping. Due to the broadcast nature of the wireless medium, devices expose their transmission attempts to passive as well as malicious nodes raising several security concerns.

One alternative to prevent eavesdropping is the use of information-theoretic security, also known as physical layer security, which allows the transmitter to send unbreakable secure messages [2]. FD communication has so far appeared as a way to boost throughput, but in this context the FD transceiver has an additional capability since it can act simultaneously as receiver and as a jammer for unintended eavesdroppers, thus improving the security and reliability of the legitimate communication link, as illustrated in Figure 5. For example, the ergodic secrecy rate with

FD communication is found to grow linearly with the logarithm of the direct channel signal power, as opposed to the flattened out secrecy rate with conventional HD communication [2].

Those gains become even more evident as the number of antennas grow or more FD nodes are available to cooperate, thus allowing for the use of relay selection, beamforming and artificial noise techniques which increases interference at the unintended eavesdroppers while simultaneously improving the performance of the legitimate link. Such gains come at a cost of self-interference and increased interference in multiple cell deployments. Nonetheless recent advances in transceiver design and self-interference mitigation have provided solutions that mitigate the interference to the noise floor, while network coordination potentially reduce the overall interference profile of the network, as discussed in Section 3.

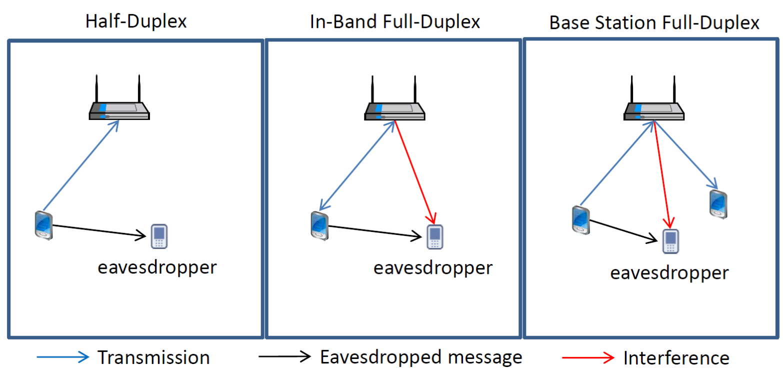


Fig. 5: Different placement of Alice, Bob and Eve under consideration in evaluating the physical layer security potential of full-duplex communication.

5.2 Cooperative communication

As discussed above, relaying is one the most successful applications of FD communication, and one more reason is that relaying allows not only to increase throughput but also solves the issue of multiplexing loss existent in HD cooperative networks, besides it is also an increased link reliability, and it is a potential solution for enhancing cell coverage. One often overlook point is that FD relaying also reduces the latency since communication is resolved within one time slot compared to its HD counterpart. Therefore, FD relaying is an attractive solution for latency-constrained applications.

However, on that case the FD relay node only acts as a helper forwarding messages from source to destination. Nonetheless, whenever the FD relay has backlog information from one or more users it can forward it together with the message being received, thus exploiting one more capability and providing in-band backhaul.

5.3 Wireless Backhaul

Backhaul, either front, mid or back haul, has become a major concern for future wireless networks, especially for dense networks where conventional solutions, such as fiber or xDSL, are not fully available or its deployment comes with an exacerbate price tag. In this context, FD appears as alternative potential solution that alleviates such costs of capital expenses and operating expenses for the network operator while providing enhanced throughput and coverage. Besides, another advantage is that the FD node can potentially allocate even traffic over both link directions, thus making better use of the transmission opportunities, improving spectral usage and reducing the latency. Therefore, FD relaying/backhaul can be an attractive solution for latency-constrained applications. Even though some efforts have been made, there are several research challenges ahead, as in smart resource scheduling and prioritization of traffic contained on distinct network functions, as well as in efficient RRM, especially for dense urban scenarios.

5.4 Cognitive Radio

In conventional cognitive radio networks the secondary users should not harm the communication of the primary network. Thus, a often used protocol first listens for primary transmissions, then if not occupied the secondary network talks, at cost of reduced transmission time due to sensing of primary network activities.

However, a transceiver operating in FD fashion can potentially increase the transmission time, while providing accurate sensing for transmission opportunities, due to its capability of simultaneous transmission and reception [15]. Moreover, collisions with primary network are potentially reduced, thus improving throughput of the primary network as well.

All in all, FD communication goes beyond increasing throughput as evinced by applications discussed in this chapter, thus rendering increased spectral efficiency, reducing collisions and enabling efficient jamming according to each application, and reducing latency as well. Several research challenges still remain though, in special with respect to network coordination so to reduce additional interference from increased FD transmissions. Traffic balancing and smart scheduling are also an open problems since traffic is preferred over one direction in current deployments, prioritization of the traffic flows are as well an open problem, in special when information flow is latency constrained. Even though the recent advances in FD communication, there are still many potential applications and challenges ahead.

6 Conclusions and Outlook

Simultaneous transmission and reception enabled by full-duplex communication promises significant throughput gains and latency reduction, and is considered as a potential 5G solution component. Under ideal assumptions, the gains of FD communication are close to 100%. However, such impressive achievements are significantly degraded in realistic network settings, primarily due to strong self-interference, resultant increase in inter-cell interference and asymmetric nature of network traffic. For example, our extensive system level simulation analysis in close-to-real-life dense network scenario shows best median gains of 15 – 20% considering the UDP traffic protocol.

Nonetheless, with efficient techniques to overcome such limitations, and application in appropriate scenarios, FD technology can be exploited to harness significant performance benefits in 5G NR, WiFi and beyond 5G networks. This chapter discusses a number of interference management techniques for FD communication, the virtual FD concept - which mimics FD communication with HD nodes - being a particular example. We show that the reliability of virtual FD can be superior than FD over the entire target SINR range with success probability gains of up to 70%. Furthermore, we show that the potential of FD technology is not limited to harnessing throughput gain and latency reduction. Rather, owing to its nature of simultaneous transmission and reception, it has valuable applications in other areas such as physical layer security, D2D communication and use cases requiring channel sensing, e.g. cognitive radios. Thus, alongside the most obvious applications in enhancing throughput and reducing latency, full-duplex communication can have niche use cases for certain applications.

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