**Abstract**

Although in cellular networks full duplex and dynamic time-division duplexing promise increased spectrum efficiency, their potential is so far challenged by increased interference. While previous studies have shown that self-interference can be suppressed to a sufficient level, we show that the cross-link interference for both duplexing modes, especially from base station to base station, is the remaining challenge in multi-cell networks, restricting the uplink performance. Using beamforming techniques of low complexity, we show that this interference can be mitigated, and that full duplex and dynamic time-division duplexing can substantially increase the capacity of multicell networks. Our results suggest that if we can control the cross-link interference in full duplex, we can almost double the multi-cell network capacity as well as user throughput. Therefore, the techniques in this article have the potential to enable a smooth introduction of full duplex into cellular systems.

**Introduction**

Cellular networks have evolved from utilizing higher frequency reuse factors to universal frequency reuse, that is, neighboring cells utilize the same frequency band in the same link direction, separated in frequency or in time. To meet the service requirements due to the ever increasing mobile data traffic [1], it is time to rethink the current reuse-1 and push the limits of spectrum reuse further. Although multiple-input multiple-output (MIMO) transmission is already used to enhance the spectral efficiency by means of frequency reuse across spatial or antenna dimensions, with the extension of multi-user MIMO (MU-MIMO), we focus on a parallel approach. Specifically, we consider dynamic time-division duplexing (D-TDD) transmissions, which increase the resource efficiency, and full duplex (FD) transmissions, which have the potential to double the system capacity by means of reuse-1/2.

D-TDD is similar to static time-division duplex (TDD) in using one direction at a time in a cell, but in D-TDD this direction can be chosen dynamically, and in theory exactly adapted to traffic needs. This straightforward extension of TDD would not only yield 100 percent capacity improvement, but would also increase efficiency because all resources can be given to a user when it is scheduled [2]. In contrast, full duplex (FD) systems in which the base station (BS) is FD and the users are half duplex (HD), are reuse-1/2 because they can use the same time-frequency twice in a cell to schedule users in both uplink (UL) and downlink (DL) directions. Realizing such FD networks in practice would be extremely useful to increase capacity in heavily loaded networks [3].

In current frequency-division duplex (FDD) or TDD configurations, the interference is of the same type as the signal: from other BSs in the DL or from other user equipment (UEs) in the UL. This normally ensures that the signal level is relatively higher than each interference level, and links can be maintained through adequate modulation and coding. However, since only one direction is set for a certain time-frequency resource, the spectral efficiency is limited to that of reuse-1 systems. At most, the share of UL or DL resources can only be partially allocated to a user, but not all. While the spectrum usage is further optimized by means of D-TDD and FD communications, additional interference management is necessary in order to harvest these benefits.

In this article, we analyze the importance of inter-cell interference suppression for FD and D-TDD transmissions. Specifically, we show that the interference between BSs is the limiting factor of the performance of FD and D-TDD. We analyze current interference mitigation techniques from both academia and industry, and propose a low-complexity solution to mitigate the interference from neighboring BSs. The numerical results show high throughput gains for the system and individual UL and DL users in different traffic scenarios. With proper inter-cell interference mitigation, we show that FD transmissions are close to theoretical doubling of the system throughput.

In the following section, the interference situation of D-TDD and FD is analyzed, and the cross-link interference (CLI) between BSs is identified as the limiting factor. Following that, mitigation techniques for the interference are discussed, and then it is shown how null-forming in the BS transmissions can suppress the interference and bring D-TDD and FD into an efficient region. The final section gives an overview of the lessons learned and perspectives for future works.
OVERVIEW OF DYNAMIC TDD AND FULL DUPLEX COMMUNICATIONS

INTERFERENCE TYPES

D-TDD cellular systems experience two kinds of inter-cell interference beyond those of static-TDD: BS-to-BS interference between DL and UL BSs, and UE-to-UE interference between users in UL and DL cells [2]. Both types of interference are referred to as inter-cell CLI (Fig. 1). In FD cellular systems with an FD BS and HD users, the additional interference beyond those of D-TDD are the self-interference (SI), that is, intra-cell interference from the BS to itself, and the intra-cell UE-to-UE interference from UL users to DL users, referred to as intra-cell CLI. To harvest the benefits of D-TDD and FD, these additional interference sources need to be mitigated. Inter-cell CLI is present in both duplexes, meaning that a solution for managing CLI in D-TDD would help for FD, and vice versa. As we show, setting SI aside, inter-cell CLI is the dominant issue, and once efficient suppression is in place, good performance can be achieved for FD and D-TDD.

DYNAMIC TDD

Unlike FDD, TDD cellular systems have the potential to increase efficiency by adapting the UL and DL time resources according to the traffic load. By using different TDD patterns dynamically across cells, under lower traffic loads, near doubling of bit rates over FDD can be expected under lower traffic loads due to the wider bandwidth used. At higher loads, queueing delay in the desired direction is expected to reduce the performance down to that of FDD, and more so if traffic is highly asymmetric in one direction. As shown on the right of Fig. 1, D-TDD allows for a scheduler to dynamically set the direction to serve UL user A or DL user B.

The authors in [4] characterized the impact of CLI in terms of the statistics of signal-to-interference-plus-noise ratio (SINR) and spectral efficiency for a small cell network. Specifically, by transforming the part of strong DL interference into weak UL interference, D-TDD is shown to improve the DL SINR with respect to TDD. Conversely, the UL performance of D-TDD is severely impacted as part of the weak UL interference becomes strong DL interference.

FULL DUPLEX COMMUNICATIONS

FD has not been considered a viable communication solution so far due to high SI. Recent advancements in antenna and analog/digital SI cancellation techniques demonstrate suppression up to 110 dB [5, 6]. To achieve the required SI suppression with reasonable form-factors, FD is primarily studied in the context of short-range communication, featuring lower transmit powers, such as in WiFi/small cells, by utilizing multiple antennas. It is important to understand the challenges involved in adapting full duplex from an isolated link to the network level, and a viable system-level solution — in terms of hardware complexity and form-factors at the transceivers — is to use full duplex only at the multi-antenna BSs, while the UEs are still operating in HD mode. The left of Fig. 1 shows this setup, with one user B in the UL and one user A in the DL. Using FD communication in the BS, there is both intra- and inter-cell CLI on UL-DL users, SI at each BS, and BS-to-BS. In D-TDD, there is a trade-off between the DL-to-UL and UL-to-DL interference, that is, an increase in one type causes a decrease in the other. However, this is not the case in FD networks because the number of interference sources increases. Therefore, the SI, CLI, and conventional intra- and inter-cell interference make the system-level operation of FD very challenging.

DESIGN QUESTIONS AND CHALLENGES

FD communications experience more interference sources than D-TDD in multi-cell scenarios. Nevertheless, due to the low-power transmission between UEs and the SI cancellation advancements, CLI, especially the BS-to-BS interference, can be the key challenge to the application of FD communications in current cellular systems. Figure 2 shows, along the arrows, the expected best use of HD, D-TDD, and FD in multi-cell networks as a function of suppression capability. Suppressing CLI enables D-TDD, while FD requires suppression of the SI as well. The arrow indicates steps of expected technical advancement.

FIGURE 2. Regions of expected best use of HD, D-TDD, and FD in multi-cell networks as a function of suppression capability. Suppressing CLI enables D-TDD, while FD requires suppression of the SI as well. The arrow indicates steps of expected technical advancement.
CLI management, including the coexistence mechanisms among different operators in adjacent cells, has been considered within the scope of Release-16. Specifically, subject to the minimum requirements on the levels of ACLR and ACS at the BS and at the UE, the performance (SINR and throughput) degradation is characterized in various combinations of adjacent networks formed over macro and indoor scenarios. Meanwhile, in the y-axis, FD also needs to address the further challenge of SI, but suppressing only SI does not suffice to enable use of FD. Since both technologies share a similar challenge, the path toward the implementation of tighter spectrum reuse with FD in cellular systems goes through the solution of BS isolation proposed for the D-TDD technology, which is represented by the arrow.

Strong CLI can be mitigated by various means such as coordinated beamforming and scheduling, power control, and hybrid dynamic/static DL/UL resource assignment. However, if two D-TDD or FD networks operate on adjacent channels, additional interference appears that can only be handled by suppression of adjacent-channel and interference and receiver selectivity, for example, adjacent-channel leakage ratio (ACLR) and adjacent-channel selectivity (ACS) [7].

Therefore, to deploy either D-TDD or FD technologies, it is essential to investigate RF coexistence mechanisms among different operators in co-channel and adjacent channels. Furthermore, the design of advanced mechanisms enabling interference measurements across BS-to-BS links and UL-to-DL links should be considered, which could enable efficient coexistence and handle CLI. Alternatively, CLI can be managed with carrier sense multiple access (CSMA), which is how D-TDD is enabled in WiFi, but in practice this increases the reuse since nearby cells are prevented from transmitting simultaneously.

**RECENT ADVANCEMENTS RELEVANT TO FD AND D-TDD**

**MULTI-CELL INTERFERENCE CANCELLATION TECHNIQUES**

Given the growing prevalence of MIMO technology, it is worth understanding different interference cancellation techniques for D-TDD and FD that exploit spatial pre- and post-processing of the transmitted and received signals.

The work in [8] considers massive MIMO at the BSs featuring a large number of antennas and shows that the BS-to-BS interference can be made arbitrarily small and bounded in principle. On the other hand, [9] exploits 3D beamforming with antenna horizontal and vertical radiation patterns being dependent on the spatial distribution of users’ locations. Specifically, the DL-to-UL and the UL-to-DL interference-to-signal ratios are characterized based on the analytical model developed for 3D beamforming.

In [10], the authors exploit a combination of MIMO interference alignment and power control to support self-backhauling in small cell networks. Linear programming is utilized to derive the feasibility conditions for interference alignment in an FD network, while power control is solved via convex optimization with the goal of maximizing the sum rate. In [11], the authors consider linear beamforming techniques for massive MIMO systems, and analyze the pilot overhead problem for cooperative and non-cooperative multi-cell scenarios using a central unit through the fronthaul. The results indicate that FD outperforms HD with an increasing number of transceiver RF chains, and that the fronthaul capacity limits the sum rate and accuracy of the channel estimation in the cooperative FD system. In [12], the authors propose interference cancellation for the BS-to-BS interference based on null forming the elevation angle at the BS antennas. Due to broad cancellation over the azimuth and into a specific and predetermined elevation angle, there are losses in the signal power in the direction of elevation angle. In [13], the authors compare the performance of HD, D-TDD, and FD for an indoor scenario operating on millimeter-wave and using successive interference cancellation to remove the strongest interference from the BS and users. The results indicate that FD outperforms D-TDD and HD depending on the SI cancellation level, and when the access point power is transmitting on a similar level as the UL users.

In contrast to the above complicated schemes, it is desirable to analyze the practical solutions proposed in the context of D-TDD transmissions and tailor them to FD communications, which is precisely discussed in the next section.

**3GPP 5G NR STUDIES ON RF COEXISTENCE IN D-TDD NETWORKS**

Fifth generation (5G) New Radio (NR) is aimed at supporting dynamic DL/UL assignments based on instantaneous traffic demands. However, none of the CLI management techniques and coexistence requirements are explicitly included in the initial Release 15 specifications. To address this, the CLI management, including the coexistence mechanisms among different operators in adjacent cells, has been considered within the scope of Release 16. Specifically, subject to the minimum requirements on the levels of ACLR and ACS at the BS and at the UE, the performance (SINR and throughput) degradation is characterized in various combinations of adjacent networks formed over macro and indoor scenarios. The following recommendations are provided based on the simulations conducted by various companies [14]:

- **D-TDD** does not seem to be viable due to the performance degradation observed in the macro-to-macro scenario.
- Two D-TDD networks with sufficient isolation operating over indoor and macro scenarios do not cause performance degradation.
- Similarly, two D-TDD indoor networks do not cause any performance degradation, provided the BS and UE power levels are on the same order and the BSs are placed judiciously by means of coordination between operators.

Therefore, D-TDD with the above-mentioned measures can be used in indoor scenarios, but not in macro scenarios.

**TOWARD FULL DOPLEX COMMUNICATIONS THROUGH DYNAMIC-TDD**

**SYSTEM PERFORMANCE IN UL WITH AND WITHOUT INTERFERENCE SUPPRESSION**

To gain insights about the required interference suppression and traffic dependence, we conduct system-level performance comparison of HD, D-TDD, and FD networks, with focus on relative comparison rather than absolute numbers. We consider a simulation of a macrocell network consisting of 7 tri-sector BSs, placed 500 m apart in a hexagonal grid. Each BS is equipped with an 8 x 8 cross-polarized antenna array, using 2 x 2
single-user MIMO. The BS antenna height is 25 m and transmit power is 40 W, while the carrier frequency is 3.5 GHz and system bandwidth is 40 MHz. Notice that in FD communications, 40 MHz is reused for both UL and DL, and split separately between the UL and DL users. For D-TDD, 40 MHz is also used for UL and DL and split jointly among all UL and DL users in the cell. Conversely, the HD mode considers 20 MHz FDD band separately for UL and DL, which is divided between UL and DL users in the cell. To gather statistics, 3000 UEs are deployed randomly outdoors with an antenna height of 1.5 m and maximum 0.2 W power targeting 10 dB signal-to-noise ratio (SNR) at the BS. The path loss follows the International Telecommunication Union (ITU) urban-macro outdoor scenario [15], corresponding to good coverage but highly unfavorable to FD communication. We assume equal traffic load across the users and that the DL load equals twice the UL load in an uncorrelated manner, and each user experiences a set of random interferers subject to the traffic levels in the DL and UL. For D-TDD, the UL/DL direction is set in each cell based on the randomly arriving traffic with the mentioned distribution.

The performance of an HD (TDD/FDD) network operating over paired 20 + 20 MHz spectrum for UL + DL is contrasted with the performance of D-TDD and FD with no suppression of CLI and SI. The unsuppressed SI is assumed to occur with 0 dB intra-cell loss, and intra-site CLI, that is, UL-to-DL user interference is assumed with 60 dB loss, corresponding to TX and RX side lobe levels. Figure 3 shows the UL throughput at the cell edges (5 percent) as a function of the increasing UL traffic, which shows that interference degrades the performance already at lower traffic loads, and is a more important factor than bandwidth. When CLI is artificially suppressed by 70 dB, the D-TDD performance improves significantly, while the FD performance improves only partly and requires additional SI suppression of 140 dB for performance on par with D-TDD. Moreover, SI suppression of as much as 140 dB without CLI suppression does not provide performance gains. Therefore, mitigation of both CLI and SI is key to improving the performance of FD.

Performance under Interference Management

Next, we consider the system-level performance of an FD system featuring interference suppression in a favorable urban-macro scenario, where 7 BSs are arranged 200 m apart in a hexagonal grid. Each BS is equipped with a 128-antenna array directed toward the served UE with 2 antennas and 1 stream, corresponding to a large cylindrical array in practice. The BS antenna height is 10 m and transmit power is 1 W, while the carrier frequency is 3.5 GHz and the system bandwidth is 40 MHz. The frequency splitting between FD, D-TDD, and HD is the same as above, and the path loss and Rayleigh fading models follow the guidelines in [15]. The SI channel is modeled as Ricean fading with a strong line-of-sight link and SI cancellation of 110 dB, where high cancellation has been shown experimentally for MIMO [5, 6]. Equal power allocation is considered in the DL with an SINR cap of 30 dB, while UL power is as described earlier.

We assume traffic loads follow an M/M/1 queue modeling and can be divided as medium and low by varying the probability that a user participates in the transmission. The medium- and low-traffic settings correspond to UL-DL cell utilization of 50 and 10 percent, respectively. We assume a scheduling policy such that one UL user and one DL user share the time-frequency resource without any multi-user intra-cell interference. The remaining inter- and intra-cell CLI between users and the BSs is present due to the sharing of the same time-frequency resource in the same or across neighboring cells. A zero forcing (ZF) precoder is used at the transmitter for FD, D-TDD, and HD. For D-TDD, the UL and DL cells are assigned dynamically to the UL/DL direction is set in each cell based on the UL and DL load in an uncorrelated manner, and each user experiences a set of random interferers subject to the traffic levels in the DL and UL. For D-TDD, the UL/DL direction is set in each cell based on the randomly arriving traffic with the mentioned distribution.

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We propose a CLI interference management method called BSint, based on the ZF receiver utilizing the BS-to-BS link channel state information (CSI), which is obtained by means of pilots and information exchange via X2 interface. Using this channel information, the receiver at the BS points a null in the direction of the BSs interfering the BS. The spatial degrees of freedom are thereby used for interference suppression instead of scheduling multiple UEs. With this, the BS can accurately cancel the BS-to-BS interference coming from at most M DL interfering BSs, where M is the number of receive antennas at the BS, and without harming the received signal power as in [12]. Notice that BSint is a low-complexity solution that can be applied to either D-TDD or FD, and that it is much simpler than the other CLI management solutions analyzed above. Overall, we compare the performance of 7 algorithms (specifically, the 50th percentile of the curves): FD, FD with BSint on 4 and 6 BSs, D-TDD, D-TDD with BSint on 4 and 6 BSs, and HD.

Figure 4 compares the cumulative distribution function (CDF) of UL interference for scenarios including FD, FD-4BSint, and FD-6BSint. Specifically, Fig. 4a shows that the BS-to-BS interference,
Recently, D-TDD and FD have appeared as technologies that can push the reuse from 1 to 1/2. Despite the similarities between FD and D-TDD, the application of FD transmissions in cellular systems has not advanced yet due to the harsher interference situation.

and not the SI, is the highest interference source in the UL of FD. With FD-4BSint, the BS-to-BS interference is completely suppressed in approximately 86 percent of cases. Hence, there are at most four interfering BSs in each resource in most cases. For FD-6BSint, the BS-to-BS interference is fully cancelled, that is, the CLI curve is far to the left. The results show that for medium traffic, the FD-4BSint solution is sufficient to cancel the vast majority of the UL CLI, and that after its cancellation, the noise and SI become the strongest interference sources. In the low-traffic scenario, FD-4BSint is expected to have performance much closer to FD-6BSint than in medium traffic due to fewer interfering sources, which is not presented due to lack of space.

In Fig. 5, we show the CDF of the system, and the individual throughput in a medium-traffic scenario for both UL and DL. FD transmissions outperform HD and the D-TDD solutions (Fig. 5a). The relative throughput gain between HD and HD is 60 percent, whereas the relative gain to D-TDD is 17 percent. Using the FD-4BSint and FD-6BSint solutions, FD provides further gains over HD and D-TDD. The relative throughput gains are 91 and 39 percent, respectively, and there is not much difference between FD-4BSint and FD-6BSint. This behavior happens because the BSs’ interference is almost cancelled when FD-4BSint is used (Fig. 4).

For the UL users in Fig. 5b, FD is outperformed by HD and all D-TDD solutions. For instance, the relative difference between FD and HD is 38 percent, while the difference to D-TDD is 27 percent. Nevertheless, FD-4BSint and FD-6BSint outperform HD and D-TDD in 39 and 67 percent, respectively, whereas their performance gains are 3 percent compared to the D-TDD solutions with CLI cancellation. With proper BS-to-BS interference suppression, FD transmissions provide higher throughput for UL users than HD and all D-TDD solutions. For the DL users in Fig. 5c, the curves have a staircase shape because of the SINR cap and frequency splitting. The relative throughput gains of FD transmission compared to HD and D-TDD are 73 and 16 percent, respectively. The gains with FD are much higher in the DL, which shows that the UL-to-DL CLI is not a limiting factor on the performance of FD. The reasons for this behavior include: the UEs have directional transmissions; transmitted power is designed to target 10 dB SNR with lower maximum transmit power than the BS; there is lower elevation, thus increasing the path loss among UEs; and, importantly, the UEs have a lower probability of a certain nearby UE being active in a certain resource block. Since the interference suppression is focused only on the BS-to-BS interference at the UL, FD-4BSint and FD-6BSint perform as the FD. Hence, in medium traffic FD provides high sum throughput gains compared to HD and D-TDD, and FD improves the throughput of both UL and DL. With proper CLI management, the gains are even higher and approach the desired doubling of the sum throughput.

In Fig. 6, we show the CDF of the system, and the individual UL and DL users throughput in a low-traffic scenario. Similar to medium traffic, in Fig. 6a the FD solution outperforms the HD and D-TDD solutions. However, the throughput gains compared to the D-TDD solutions is much lower now, 4 percent; whereas the gains to HD are high, 72 percent. The reason for high gains compared to HD is the resource utilization in the low-traffic scenario. Most resources are occupied by a single UL or DL user, which uses the whole bandwidth of 40 MHz instead of the bandwidth of 20 MHz. Due to the same reason, the performance gain compared to D-TDD is much lower than in medium traffic, and both FD-4BSint and FD-6BSint have the same performance in terms of sum throughput. Nevertheless, the relative gain is 20 percent between HD, FD-4BSint, and FD-6BSint. Moreover, FD-4BSint and FD-6BSint have a relative gain of approximately 99 percent compared to HD, which shows that CLI management yields almost doubling of the sum throughput. FD transmissions benefit from the low-traffic scenario due to low resource usage between UL and DL users, and CLI management further improves these benefits.

For the UL users in Fig. 6b, FD is still outperformed by HD and all D-TDD solutions. As in Fig. 5b, the solutions FD-4BSint and FD-6BSint perform much better than HD. Their relative performance gains compared to HD and D-TDD are 93 percent. When comparing FD-4BSint and FD-6BSint with D-TDD-4BSint and D-TDD-6BSint, the relative gains are much smaller and close to 1 percent. This behavior shows that in low traffic and with enough CLI cancellation, the UL performance of FD and D-TDD are almost the same. Hence, the BS-to-BS interference suppression provides higher gains in low traffic than in medium traffic. For the DL users
in Fig. 6c, the performance is similar to that of medium traffic in Fig. 5c.

We generated results for lower levels of SI cancellation, such as 90 dB, where we noticed that the BS-to-BS interference is still crucial together with the SI. Due to space limitations, we do not include these results. Neither the system nor the DL throughput are impacted, only the UL throughput, which is slightly outperformed by D-TDD with BS-to-BS interference cancellation. Hence, cancel- lations ≤ 90 dB limit only the UL performance.

Overall, the BS-to-BS interference is the highest source of interference in a multi-cell scenario provided the SI is sufficiently cancelled. With proper BS-to-BS interference, FD brings throughput gains for both UL and DL users in different traffic scenarios and can almost double the throughput for the system and individual users.

**Conclusions, Lessons Learned, and Perspective**

Recently, D-TDD and FD have appeared as technologies that can push reuse from 1 to 1/2. Despite the similarities between FD and D-TDD, the application of FD transmissions in cellular systems has not advanced yet due to the harsher interference situation. In this article, we argue that the key limitation is not SI, but CLI on the UL, that is, BS-to-BS interference, which we validate by means of simulations. To support a smooth implementation of FD transmissions in current networks, we discuss the relevant studies and signaling measurements already standardized for D-TDD. Using these ideas, we propose a low-complexity receiver that mitigates the CLI at the receiving BS by exploiting the BS-to-BS link CSI. We show that FD under CLI management greatly outperforms HD and D-TDD for medium- and low-traffic scenarios in terms of system and individual throughput for UL and DL users.

From our results, we can summarize the lessons learned as follows:

- With the high SI cancellation achievable in current MIMO systems, the BS-to-BS interference, and not the SI or UL-to-DL interference, is the limiting factor in FD cellular networks.
- Medium- and low-traffic scenarios benefit from FD transmissions due to the efficient spectrum reuse across cells.
- D-TDD also gives efficiency gains, especially in low-traffic scenarios.
- CLI management is essential for providing high UL throughput gains.
- Low-complexity receivers suitable for both D-TDD and FD are possible and may help to realize FD cellular networks.

To achieve the CLI management discussed in this article and realize efficient D-TDD and FD in a 5G multi-cell system, measurements between BSs would be required to estimate CSI. Recent work on CLI [14] has not resulted in specification of the required enabler techniques in terms of coordination or measurements. Given that BSs are stationary and interference is co-channel, both direct measurements on probes from the victim BS in the source BS and vice versa and exchange of results appear feasible. The high level of suppression calls for highly accurate ZF and frequent estimates, which is possible with slight increase of overhead and computing costs.
Interesting topics for future research include the importance of CSI, and the necessary accuracy in suppressing CLI to realize efficient D-TDD and FD in a 5G multi-cell system. When this is achieved, along with accurate SI suppression, FD can become a next evolutionary step in spectrum reuse.

A different approach is to use the antenna correlation at the BSs to accurately estimate the strongest direction of the channel between each source BS and victim BS. Using this idea, it is not necessary to account for the beamforming of each DL user in the source BS. This approach is similar to [12], but more specific due to use of the directions of interfering source BSs, and without harming the received power. In situations where obtaining accurate CSI is complicated, a possibility is to estimate the channel from other source BSs and form an average over their used beams toward the victim BS.

Interesting topics for future research include the importance of CSI, and the necessary accuracy in suppressing CLI to realize efficient D-TDD and FD in a 5G multi-cell system. When this is achieved, along with accurate SI suppression, FD can become a next evolutionary step in spectrum reuse. Another interesting topic for future study is the suitability of cell-free massive MIMO and its central processing for CLI suppression to see if FD is a better use of the antenna degrees of freedom than MU-MIMO, and if both techniques can be combined.

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BIOGRAPHIES
JOSE MAIRTON B. DA SILVA JR received his Ph.D. degree in electrical engineering and computer science from KTH Royal Institute of Technology, Sweden, in 2019. He received his B.Sc. (with honors) and M.Sc. degrees in telecommunications engineering from the Federal University of Ceará, Brazil, in 2012 and 2014. During fall/winter of 2013–2014, he worked in an internship at Ericsson Research, Sweden. During spring/fall 2018, he was a visiting researcher at Rice University. He is currently a postdoctoral researcher at KTH Royal Institute of Technology and the Secretary of the IEEE ETV on Full Duplex Communications. His research interests include machine learning and optimization over wireless communications.

GUSTAV WIKSTRÖM is a research leader at Ericsson Research Networks, focusing on the next generation of networks. He joined Ericsson in 2011 after postdoctoral studies in physics, and has worked with standardization, concept development, and performance evaluations for WLAN, 4G, and 5G.

RATHESH K. MUNGARA received his Ph.D. degree in information and communication technologies from Universitat Pompeu Fabra, Barcelona, Spain, in 2016. He was a postdoctoral researcher at Technische Universität Berlin, Germany, during 2017–2018. He is currently a senior researcher with the Radio Department of Ericsson Research, Stockholm, Sweden. His general research interests are communication-theoretic modeling and analysis of wireless networks, with a specific focus on multi-antenna communication and interference management.

CARLO FISCHIONE received his Ph.D. degree in electrical and information engineering (3/3 years) in 2005 and his Laurea degree in electronic engineering (summa cum laude, 5/5 years) in 2001, both from the University of L’Aquila. He is a full professor at KTH Royal Institute of Technology, Electrical Engineering and Computer Science, Division of Network and Systems Engineering. His research interests include machine learning, wireless networks, the Internet of Things, and machine learning. He cowrote the IEEE Communications Society Stephen O. Rice best paper award of 2018. He is an Editor of IEEE Transactions on Communications, Associate Editor of the IEEE Journal on Selected Areas on Communications, Machine Learning for Communication and Networking, and Chair of the IEEE ETV Machine Learning for Communications.