

Full Duplex Cellular Systems: Will Doubling Interference Prevent Doubling Capacity?

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Abstract

Recent advances in antenna and RF circuit design have greatly reduced the crosstalk between the transmitter and receiver circuits on a wireless device, which enable radios to transmit and receive on the same frequency at the same time. Such a *full duplex* (FD) radio has the potential to double the spectral efficiency of a point-to-point radio link. However, the application of such a radio in current cellular systems (3GPP LTE) has not been comprehensively analyzed. This article addresses the fundamental challenges in incorporating FD radios in a cellular network to unlock the full potential of FD communications. We observe that, without carefully planning, FD transmission might cause much higher interference in both uplink and downlink, which greatly limits the potential gains. Another challenge is that standard scheduling methods that attempt to achieve the maximum capacity gain lead to a severe loss in energy efficiency. In this article, we identify new tradeoffs in designing FD enabled radio networks, and discuss favorable conditions to operate in FD mode. New scheduling algorithms and advanced interference cancellation techniques are discussed, which are essential to maximize the capacity gain and energy efficiency. Under this new design, most of the gain is achievable with FD enabled base stations (BSs), while user equipment (UEs) still operate in the half duplex (HD) mode.

I. INTRODUCTION

Cellular networks have entered a period of unprecedented change and ever-increasing importance to the economy and society. To support the exploding demand for video and other high-rate data services, such networks have begun a major shift from being voice-centric, circuit-switched and centrally optimized for coverage, towards being data-centric, packet-switched and organically deployed for maximum capacity. Cisco's well-known capacity forecasts estimate that mobile data will grow eleven-fold in the period 2013-2018 [1]. Such drastic changes are largely due to new trends in usage, with smartphones in particular leading to a proliferation of data-hungry applications. Full duplex (FD) technology, which has the potential to double the spectrum efficiency, provides a step towards meeting high demand without requiring new spectrum.

Traditional radio transceivers are generally not able to receive and transmit on the same frequency channel simultaneously because of the crosstalk between the transmitter (Tx) and the receiver (Rx). Given that the intended received signal over-the-air can be more than a million times weaker than the transmitted signal due to path loss and fading, it is very difficult, if not impossible, to detect the received signal under internal interference from the transmission circuits and antennas. Thus, most of today's communication systems are half duplex (HD) in each channel; while bidirectional transmissions are based on two orthogonal channels, typically using time (Time Division Duplex or TDD) or frequency dimensions (Frequency Division Duplex or FDD), to provide separation between transmit and receive signals.

Recent advances in antenna design and RF circuits [2-6] have made a great leap forward in reducing self-interference (SI) between the Tx and Rx circuits on a common channel. New antenna designs, combined with analog and digital cancellation, are employed to remove most of the SI from the Rx path to allow decoding of the desired received signal. This was demonstrated using multiple antennas positioned for optimum cancellation [2-4] and later for single antenna systems [5][6]. Jain *et al.* [3] used the combination of signal inversion and digital cancellation which achieves 73 dB of cancellation for a 10 MHz OFDM

signal. In other work, a combination of passive, analog, and digital cancellation achieved a median cancellation of 85 dB, with a minimum of 70 dB and a maximum of 100 dB over a 20 MHz WLAN channel [4]. An antenna feed network was proposed by Knox [5], a prototype of which provided Tx/Rx isolation of 40-to-45 dB before analog and digital cancellation. Bharadia *et al.* [6] proposed a single antenna design which is able to achieve up to 110 dB of cancellation over an 80 MHz bandwidth.

Although extensive efforts have been made in designing and implementing wireless terminals with FD capability, to the best of our knowledge, the impact of FD transmissions in a wireless network in terms of system capacity and energy efficiency has not been extensively analyzed, especially in a cellular environment. FD operation in a cellular small cell system has been investigated in the DUPLO project [7]. This work is mostly focused on the joint uplink and downlink beamforming design in a single cell. Alves *et al.* [8] derived average spectral efficiency for a stochastic geometry based dense small cell environment with both BS and UEs having FD capability. These analyses do not consider the multi-UE diversity gain, which comes through scheduling of the appropriate UEs with power adjustments to mitigate inter-node interference.

Given the premise that sufficient SI cancellation (SIC) is feasible, this article considers access links of a multi-cell system, where the base stations (BSs) have the capability of FD operation, and user equipment (UEs) is limited to HD operation. Since FD requires a significant change in the hardware with higher cost and power usage, it is more practical to upgrade the infrastructure elements. Hence, our preferred FD cellular system will have the above assumption, that is, FD BSs and HD UEs, unless specified otherwise.

In the FD cellular system, as shown in Figure 1, each BS can simultaneously schedule the uplink and downlink transmission on the same resource block. Therefore, each transmission potentially experiences higher interference from within the cell and from neighboring cells, compared to the traditional HD cellular systems. The high interference in each direction raises several questions regarding the potential performance of FD operation in a cellular system. Even in a single cell, FD gain cannot be achieved without careful selection of the uplink and downlink UEs for simultaneous transmission [9]. The focus of

this article is: (1) identifying the new interference scenario in FD cellular systems, (2) finding a suitable cellular environment to deploy FD radios, (3) proposing a new proportional fairness-based hybrid scheduling algorithm, (4) analyzing and proposing techniques to address energy efficiency. It should be mentioned that, in this article, we assume omnidirectional transmission and reception of the signals at all BSs and UEs. Using directional transmission and reception, which may be achieved by beamforming with multiple antennas or other PHY layer techniques, can certainly change the interference situation mentioned above. Interference mitigation at PHY layer is out of the scope of this article, and will be discussed in our future work.

The rest of the article is organized as follows. Section II introduces the FD cellular system. Section III categorizes and discusses the impact of each of the new interference sources during FD operation. The design of a scheduling algorithm, which minimizes interference and maximizes FD gains, is described in Section IV. The impact of FD on energy efficiency is provided in Section V. Section VI concludes the article.

II. FULL DUPLEX OPERATION IN A CELLULAR ENVIRONMENT

Figure 1 illustrates FD operation in a multi-cell environment, and compares it to traditional TDD/FDD operation. In this figure, a two-cell network with two UEs in each cell is considered. UE1 and UE3 are in downlink mode while UE2 and UE4 are in uplink mode. In this section, for illustration purposes, we assume a *synchronous* HD multi-cell deployment in which, (1) in a given time slot, all cells schedule either uplink or downlink transmission, (2) the number of timeslots is divided equally between uplink and downlink transmission. For simplicity, we only show the impact of interference on users of cell 1. In HD operation, as shown in Figure 1(a), in the downlink, UE1 gets interference (I_1) from BS2, which is transmitting to UE3 at the same time. Similarly, in the uplink, as shown in Figure 1(b), BS1 gets interference (I_2) from the uplink signal of UE4. Figure 1(c) shows the impact of FD operation on both inter-cell and intra-cell interference, where both BS1 and BS2 transmit in FD mode and each one schedules a

downlink and an uplink UE simultaneously. During FD operation, in the downlink, UE1 gets interference (I_1) from BS2 and interference (I_3 and I_4) from the uplink signals of UE2 and UE4. Similarly, in the uplink, BS1 gets interference (I_2) from UE4 and interference (I_6) from the downlink signal of BS2, as well as Tx-to-Rx SI (I_5).

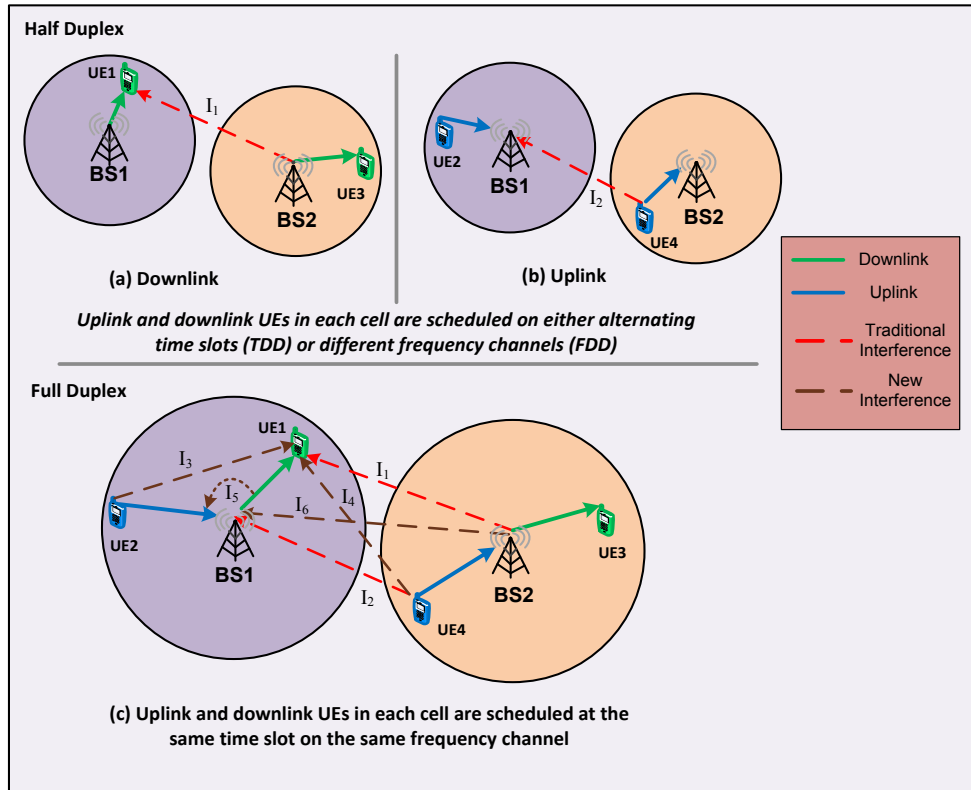


Figure 1. Half duplex and full duplex multi-cell scenarios.

In downlink, the additional interference during FD operation comes from all the active uplink UEs on the same channel, which we call *UE-to-UE interference*. In uplink, additional interference comes from (1) Tx-to-Rx SI, which we will simply refer to as *self-interference (SI)* at its own BS, and (2) neighboring BSs due to a simultaneous downlink transmission, which we call *BS-to-BS interference*. In the next section, we discuss the nature of each of these additional interference sources in detail.

III. INTERFERENCE DURING FULL DUPLEX OPERATION

A. BS-to-BS interference

The path loss between BSs is generally much smaller than the path loss between BSs and UEs, especially in an outdoor environment, where BSs are usually installed at higher elevations and have fewer obstructions and less absorption in between them [10]. When coupled with large transmission power from BSs, this interference becomes very strong. Techniques to mitigate BS-to-BS interference are necessary to realize FD BSs deployment, especially in outdoor environments. The issue of BS-to-BS interference is well discussed in the 3GPP documents on dynamic TDD HD deployment [11]. Some methods to mitigate BS-to-BS interference include null forming in the elevation angle at BS antennas [10], and interference management through the Cloud Radio Access Network (C-RAN) architecture [12].

B. Self-interference (SI)

Although there has been a significant effort in improving cancellation circuits, the applicability of FD radios in large cells is still questionable. For example, consider a cell with 1-kilometer radius, where the path loss at the cell edge is around 130 dB [11]. Assuming equal per channel transmission power at the uplink and downlink directions, the signal arriving at the BS is 130 dB lower than the signal transmitted. With the best SI cancelling circuit known to date, which is capable of suppressing the crosstalk by 110 dB [6], the received signal to interference ratio (SIR) is at most -20 dB. In a typical isolated indoor cell with a radius of about 40 meters as described in Section IV, the average received SIR with 110 dB SIC can be as high as 33 dB.

Most of the existing work on FD cellular systems [10][12] does not consider the effect of SI at BSs. In our view, unless there is a major breakthrough in the cancellation circuit design, FD operations are more practical for small cell deployment, where the smaller coverage area make it a more suitable environment to deploy FD radios.

C. UE-to-UE interference

Since this type of interference depends on the UE locations and their transmission powers, an intelligent coordination mechanism is needed. The goal of the coordination is to select those UEs for simultaneous

transmission such that their rate/power allocation would create less interference for each other.

Based on the above discussion, we suggest that: (1) A small cell environment is more suited to FD operation; (2) Intelligent scheduling of UEs with appropriate rate/power allocation is necessary to extract the capacity gain potential of FD operation.

IV. SCHEDULING IN A FULL DUPLEX CELLULAR SYSTEM

It is clear from the above discussion that simultaneous uplink and downlink transmission during FD operation comes with additional intra-cell and inter-cell interference. To achieve the potential capacity gain from FD operation, it becomes necessary to intelligently schedule an appropriate combination of downlink and uplink UEs with corresponding transmission rates/powers so that an aggregate network utility can be maximized while a level of fairness is maintained. Since pure FD transmission may not always be optimal due to the presence of extra interference, we use a hybrid scheduling algorithm where, in a given time slot in a cell, we may schedule only one downlink or uplink UE, or a pair of downlink and uplink UEs.

The scheduling algorithm consists of joint UE selection and rate allocation to maximize the performance of FD operation in a multi-cell system. A proportional fairness based utility function, similar to the one used in [9] is considered, where the objective is to maximize the joint uplink and downlink utility of the system. We assume a centralized scheduler that has access to global system information (power, channel state information). Scheduling methods with limited or no information exchange among cells will be considered in our future work.

The joint UE selection and rate allocation is a nonlinear non-convex problem with mixed discrete and continuous optimization. Finding a global optimum through an exhaustive search method is computationally difficult, so a suboptimal method is considered. This problem is solved in two steps: (1) with maximum power allocated to each UE, we select UEs based on a heuristic greedy method; (2) for the selected UEs, geometric programming [13] is used to find the optimum rates/powers, such that the aggregate utility in the objective function can be maximized. The details of the algorithm can be found in

[14].

The proposed scheduling method is simulated in a multi indoor Remote Radio Head (RRH)/Hotzone cell [15] as shown in Figure 2, along with a wraparound topology. First, we simulate the system with eight randomly dropped UEs in each cell with full-buffered traffic in both directions. BSs and UEs are assumed to be equipped with single antennas. The simulation parameters are based on 3GPP simulation recommendations [15], and are described in Figure 2. The channel model used between BSs and UEs is also used between mobile UEs and between BSs for the interference calculations, with the justification that BSs do not have a significant height advantage in the small cell indoor scenario considered. We use the Shannon equation to measure the data rate, where we apply a minimum spectral efficiency of 0.26 bits/sec/Hz and a maximum spectral efficiency of 6 bits/sec/Hz to match practical systems.

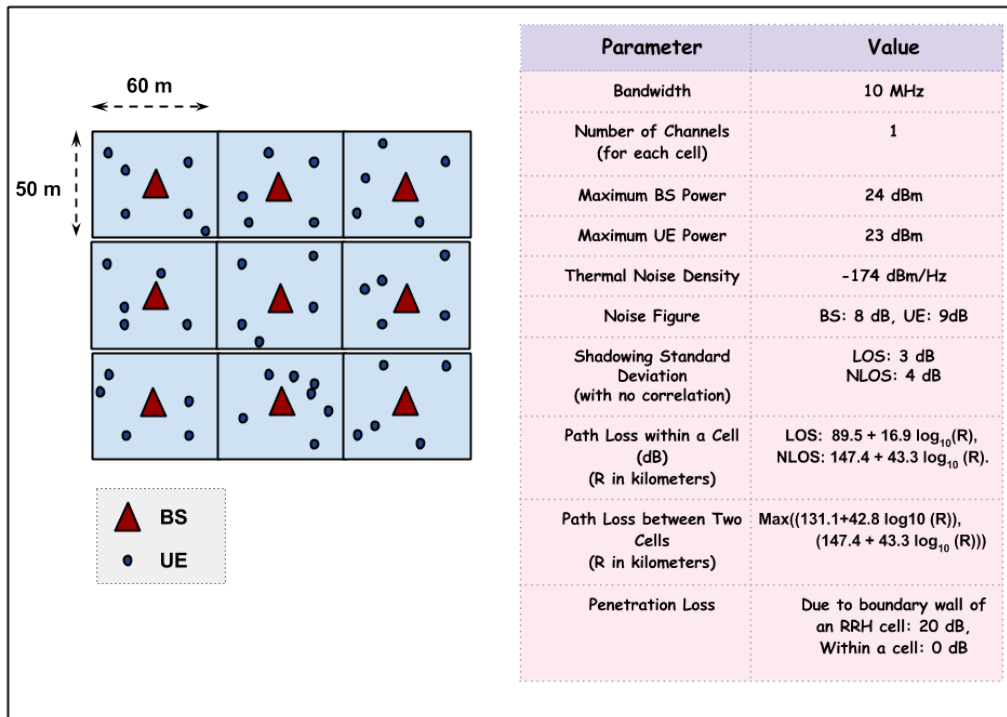


Figure 2. An indoor environment with nine RRH Cells.

With these settings, we ran our simulations for different UE drops, each with a thousand timeslots and generated results for both HD and FD systems. For the FD system, different values of BS SIC capability are considered. The residual SI is modeled as Gaussian noise, whose power equals the difference between

the transmit power of the BS and the assumed amount of SIC. For the HD system, results are generated for both synchronous and dynamic TDD operation. In the *dynamic* TDD system, each cell has the flexibility of scheduling its UE in any direction; whichever provides larger utility at the given timeslot. The distributions of average downlink and uplink throughputs for the HD and FD systems are plotted in Figure 3(a) and 3(b), respectively. The HD system shows a narrow distribution centered near 4 Mbps in both the uplink and downlink. Since the same kind of channel model is assumed between different nodes, there is not much difference in the interference experienced by a node in synchronous or dynamic TDD systems. Thus, similar results are obtained for these two systems. The FD system shows a wider distribution since the scheduler takes advantage of the random nature of the interference to assign FD operation with an appropriate data rate whenever possible. The throughput gain in both directions increases as the SIC improves. On average, downlink throughput gains of 56%, 80%, 94%, 97%, and 98% are achieved in the FD system with SIC of 75 dB, 85 dB, 95 dB, 105 dB, and no SI, respectively. Similarly, in the uplink, the corresponding gains are 63%, 83%, 93%, 96%, and 97%.

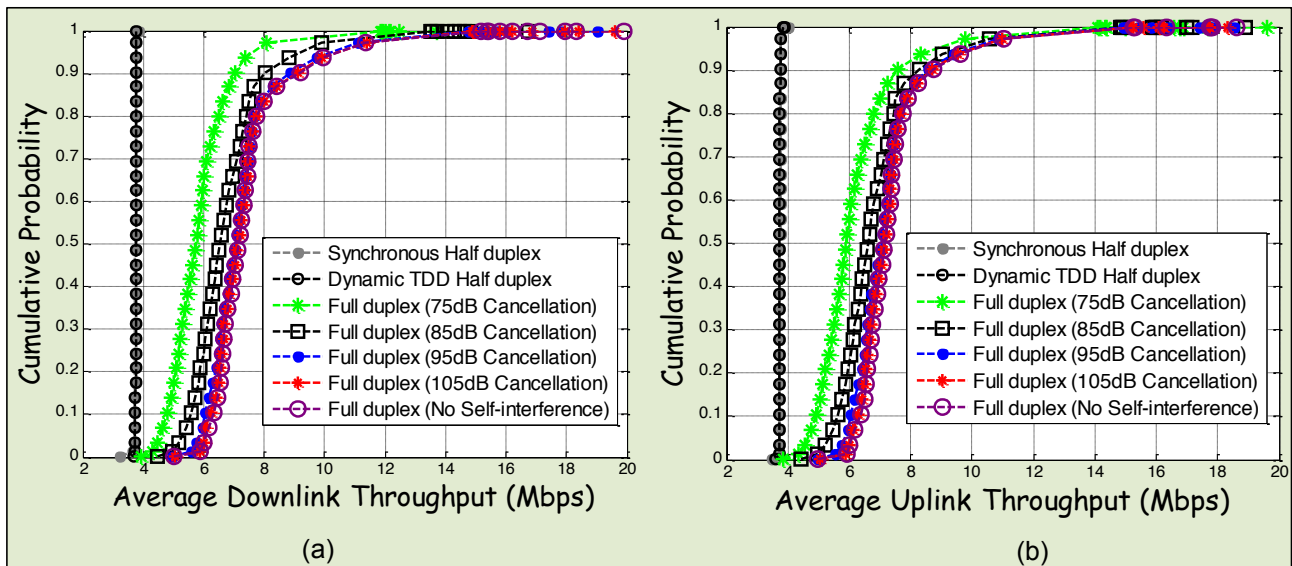


Figure 3. Distribution of average data rates for the half duplex system and full duplex system with different self-interference cancellation capabilities.

We also evaluate the system with non-full buffer FTP traffic [15], where each UE has requests to

download/upload files of 1.25 MB. The time interval between completion of a file transmission and an arrival of a new request is exponentially distributed with a mean of 1 second. We calculate the delay for each UE as the total time it experiences from the request arrival to the completion of downloading or uploading a file. Since in an FD system, downloading and uploading can take place simultaneously, a significant delay improvement is observed. On average a UE experiences 2.34 seconds of delay in the downlink and 2.39 seconds of delay in the uplink in the HD system. In the FD system, in the downlink, this delay reduces to 1.33, 1.05, 0.89, 0.83, and 0.81 seconds with 75 dB, 85 dB, 95 dB, 105 dB, and perfect SIC, respectively. Similarly in the uplink, a UE experiences 1.23, 1.01, 0.92, 0.89, and 0.87 seconds of delay with 75 dB, 85 dB, 95 dB, 105 dB, and perfect SIC, respectively. Moreover, in the FD system, a UE downloads 48%, 69%, 83%, 90%, and 92% more files and uploads 56%, 75%, 86%, 88%, and 90% more files compared to those in the HD system with 75 dB, 85 dB, 95 dB, 105 dB, and perfect SIC, respectively.

The above results show that the FD system has the potential to increase the capacity of small cells significantly. The related issue of energy efficiency during FD operation to achieve this capacity improvement, which to our knowledge has not been examined before, is presented in the next section.

In this article, we have considered symmetric downlink/uplink traffic demands. Asymmetric traffic tends to reduce the need for simultaneous uplink and downlink transmission, which decreases the potential capacity gain of FD operation. However, recent growth in online storage services (Google Drive, Dropbox, iCloud, etc.), and the increasing popularity of photo and video uploading to social networking sites, have increased, and will continue to increase, the uplink traffic volume significantly, making the traffic less asymmetric.

V. ENERGY EFFICIENCY OF THE FULL DUPLEX CELLULAR SYSTEM

As energy efficiency becomes more important in cellular system design, it is interesting to examine the energy efficiency of FD operation. Energy efficiency is calculated for each UE by dividing the total throughput by the total power consumed for signal transmission; power consumed in transceiver circuits is

not considered. The average per UE downlink and uplink energy efficiency of different systems for the full-buffer traffic case are shown in Figure 4 in Tbits/Joule. Since similar energy efficiency results are obtained for the non-full buffer case, we will consider only the full-buffer case in the following discussion. The results show that, compared to HD systems, FD systems experience a significant penalty in energy efficiency. The extra energy is used to combat the additional interference created during FD transmission. Also note that the goal of the scheduler presented above is capacity maximization while maintaining fairness; it does not try to optimize energy efficiency.

	Half duplex (Synchronous, Dynamic TDD)	Full duplex (75 dB Cancellation)	Full duplex (85 dB Cancellation)	Full duplex (95 dB Cancellation)	Full duplex (105 dB Cancellation)	Full duplex (No self- interference)
Downlink	(3.74, 4.40)	0.045	0.097	0.227	0.326	0.434
Uplink	(4.91, 4.91)	0.017	0.151	0.734	1.360	1.971

Figure 4. Average energy efficiency (terabits per joule) for downlink and uplink directions.

In general, as SIC gets better, with the reduction in SI, UE-to-UE and BS-to-BS interference increases due to the larger number of FD transmissions scheduled. Because of this trade-off phenomenon, the impact of SIC on energy efficiency is difficult to explicitly formulate. Our simulations show that uplink and downlink energy efficiency increases as SIC improves. The improvement in SIC provides a significant reduction in interference on the uplink transmission as compared to the increase in the interference due to the higher number of FD transmissions. This tradeoff results in reduced uplink transmit power, which in turn reduces the additional interference on the downlink transmission.

Since the main reason for the lower energy efficiency of the FD system is the additional power needed to combat the extra interference, two solutions can be proposed to alleviate this issue. The first solution is to cancel or mitigate the additional interference using techniques such as beamforming and sectorization. In this particular small cell indoor scenario, where most of the inter-cell interference is mitigated by penetration loss between the cells, intra-cell interference plays a dominant role during FD operation. If we

assume that sufficient SIC is available for the small cell scenario (e.g., 105 dB), allowing FD operation on the UEs (FD UEs) may remove UE to UE intra-cell interference. In this case, the BS and one UE in each cell will simultaneously transmit in both uplink and downlink directions. Thus, a downlink UE will not experience intra-cell interference from an uplink UE in the same cell. Our simulation results, shown in Figure 5, indicate that average throughput gains in such an FD system are 44%, 77%, 90%, 99%, and 100% in the downlink and 43%, 77%, 90%, 99%, and 100% in the uplink for 75 dB, 85 dB, 95 dB, 105 dB SIC, and no SI, respectively. For the lower SIC case of 75 dB, although the energy efficiency is higher as compared to the previous case of HD UEs, the throughput is lower. As cancellation improves, there is not much difference in the average throughput from the previous case, but energy efficiency improves significantly. For 105 dB SIC, in the downlink, 3.04 Tbits/joule is achieved as compared to 0.326 Tbits/joule, and in the uplink, 2.66 Tbits/joule is achieved as compared to 1.36 Tbits/joule. These results show that in the higher SIC scenario, it is beneficial to have FD UEs, especially in a small indoor environment. In this case, energy efficiency does not vary monotonically with SIC because of the trade-off mentioned earlier in this section.

	75 dB Cancellation	85 dB Cancellation	95 dB Cancellation	105 dB Cancellation	No Self-interference
Downlink	44%	77%	90%	99%	100%
Uplink	43%	77%	90%	99%	100%
Downlink	0.51	2.18	1.59	3.04	3.98
Uplink	0.31	1.60	0.86	2.66	4.08

Figure 5. Average throughput gain and energy efficiency (terabits per joule) with full duplex UEs.

A second solution to improve energy efficiency is to keep using HD UEs but implement a more intelligent scheduling algorithm in which, during the rate/power allocation step, a utility function incorporating the cost of using high power is considered, that is,

$$\text{System Utility} = \text{Total System Throughput} - \text{Weighted Total Selected UEs' Power Allocation} \quad (1)$$

In the above expression, the first term, *Total System Throughput*, is still calculated based on proportional fairness. The second term, *Weighted Total Selected UEs' Power Allocation*, is computed by applying a penalty for UEs using high power. The level of penalty varies for different UEs. For example, UEs further from the cell center should have a lower penalty than UEs closer to the center. The details of the algorithm can be found in [14].

As shown in Figure 6, this type of scheduling causes a modest loss in the throughput gain compared to the original scheduling algorithm, however, a significant improvement in energy efficiency is observed. As an example, an energy efficiency of 2.02 Tbits/joule is achieved compared to the 0.045 Tbits/joule in the downlink with 75 dB SIC.

	75 dB Cancellation	85 dB Cancellation	95 dB Cancellation	105 dB Cancellation	No Self-interference
Downlink	44%	72%	91%	95%	96%
Uplink	50%	69%	85%	89%	91%
Downlink	2.02	1.01	0.80	0.75	0.73
Uplink	1.46	2.47	3.23	3.58	3.61

← Average Throughput Gain

← Average Energy Efficiency (Tbits/Joule)

Figure 6. Average throughput gain and energy efficiency (terabits per joule) with power allocation method including a penalty for higher power consumption.

VI. CONCLUSION

Recent progress in antenna and RF circuit design to achieve cancellation of SI between Tx and Rx channels of a wireless device has made it possible to build FD radios. This article is an effort to analyze the system-wide impact of FD transmission in a cellular environment. With current state of the art interference cancellation circuits, we believe it is more feasible to operate in FD mode in small cells. In this article, we focus on an indoor small cell environment. In ongoing work [14], we show that FD is also useful in a sparse outdoor small cell environment. New sources of interference are identified in FD transmission, and we note that, if the uplink and downlink transmission are not coordinated, the added interference greatly reduces the potential gain of FD operation. Due to the hardware/cost requirement to build FD radios, we suggest a network with FD BSs and HD UEs. With our proposed proportional fairness based scheduler that jointly optimizes UEs and selects rates, we show that the system capacity almost doubles. Another challenge of FD operation is to reduce the energy consumption, since significant energy is consumed to combat the strong interference that is new to FD operation. In our view, energy efficiency could be improved either by enabling FD UEs, or using a modified scheduling algorithm that penalizes using high power during FD operation. We conclude that FD is a promising technology with the potential of significantly improving cellular system throughput.

REFERENCES

- [1] "Cisco visual networking index: Forecast and methodology 2013-2018," Cisco white paper, www.cisco.com, 10 June 2014.
- [2] A.K. Khandani, "Methods for spatial multiplexing of wireless two-way channels," U.S. Patent No. 7,817,641, 19 Oct. 2010.
- [3] M. Jain, J. I. Choi, T. Kim, D. Bharadia, S. Seth, K. Srinivasan, P. Levis, S. Katti, and P. Sinha, "Practical, real-time, full duplex wireless," in *17th Annual International Conference on Mobile Computing and Networking (Mobicom)*, 2011, pp. 301-312.
- [4] M. Duarte, A. Sabharwal, V. Aggarwal, R. Jana, K. K. Ramakrishnan, C. Rice, and N. K. Shankaranarayanan, "Design and characterization of a full duplex multi-antenna system for WiFi networks," in *IEEE Transactions on Vehicular Technology*, vol. 63, no. 3, pp. 1160-1177, March 2014.
- [5] M. Knox, "Single antenna full duplex communications using a common carrier," in *IEEE 13th Annual Wireless and Microwave Technology Conference (WAMICON)*, Cocoa Beach, FL, 15-17 April 2012, pp. 1-6.
- [6] D. Bharadia, E. McMillin, and S. Katti, "Full duplex radios," in *ACM SIGCOMM*, Hong Kong, 12-16 August 2013, pp. 375-386.
- [7] The Duplo website. [Online]. Available: <http://www.fp7-duplo.eu/>.
- [8] H. Alves, C. Lima, P. Nardelli, R. D. Souza, and M. Latva-aho, "On the Average Spectral Efficiency of Interference-Limited Full-Duplex Networks," in *IEEE 9th International Conference on Cognitive Radio Oriented Wireless Networks and Communications (CrownCom)*, Oulu, Finland, June 2014.

- [9] S. Goyal, P. Liu, S. Panwar, R.A. DiFazio, R. Yang, J. Li, and E. Bala, "Improving small cell capacity with common-carrier full duplex radios," in *IEEE International Conference on Communications (ICC)*, Sydney, Australia, June 2014.
- [10] Y.-S. Choi and H. Shirani-Mehr, "Simultaneous transmission and reception: Algorithm, design and system level performance," in *IEEE Transactions on Wireless Communications*, vol. 12, no. 12, pp. 5992–6010, Oct. 2013.
- [11] 3GPP TR 36.828, "Further enhancements to LTE time division duplex (TDD) for downlink-uplink (DL-UL) interference management and traffic adaptation," v.11.0.0, www.3gpp.org, June 2012.
- [12] O. Simeone, E. Erkip, and S. Shamai, "Full-Duplex Cloud Radio Access Networks: An Information-Theoretic Viewpoint," in *IEEE Wireless Communications Letters*, vol. 3, no. 4, pp. 413-416, August 2014.
- [13] M. Chiang, C. W. Tan, D. P. Palomar, D. O'Neill, and D. Julian, "Power control by geometric programming," in *IEEE Transactions on Wireless Communications*, vol. 6, no. 7, pp. 2640-2651, July 2007.
- [14] S. Goyal, P. Liu, S. Panwar, R. Yang, R. A. DiFazio, and E. Bala, "Full duplex operation for small cells," CoRR, vol. abs/1412.8708, 2014. [Online]. Available: <http://arxiv.org/abs/1412.8708>.
- [15] 3GPP TR 36.814, "Further advancements for E-UTRA physical layer aspects," v.9.0.0, www.3gpp.org, May 2010.

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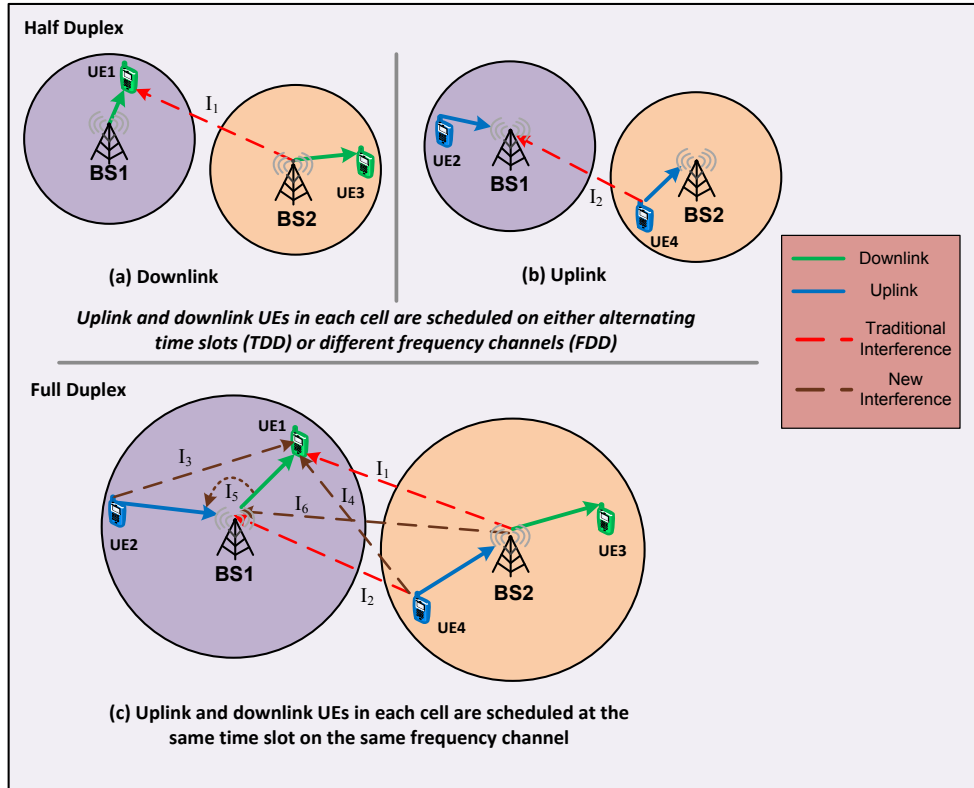


Figure 1. Half duplex and full duplex multi-cell scenarios.

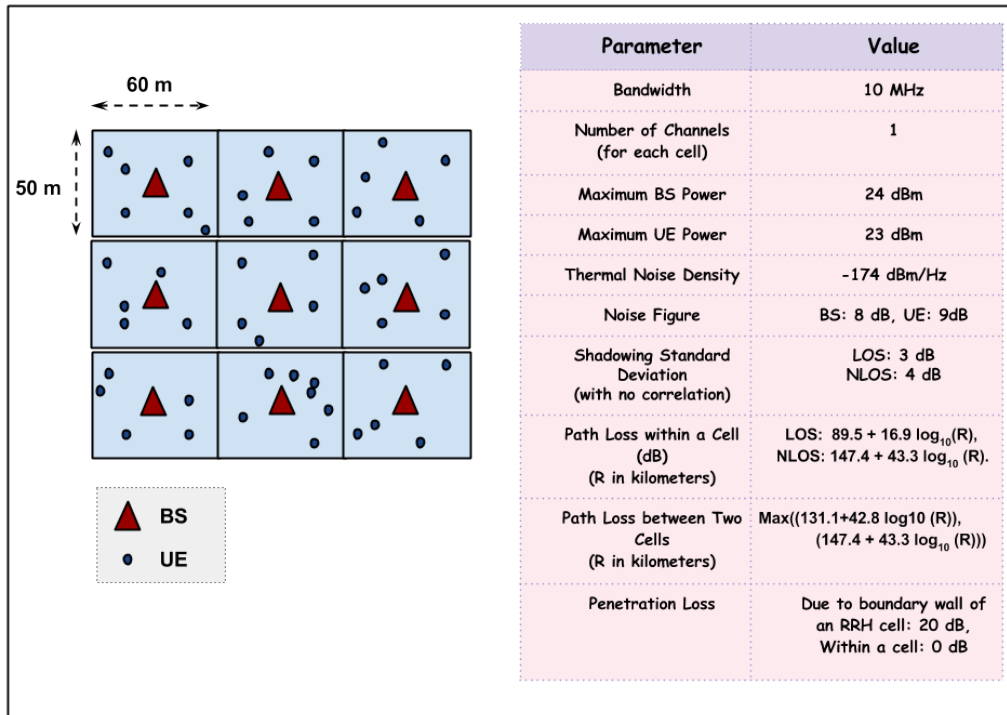


Figure 2. An indoor environment with nine RRH Cells.

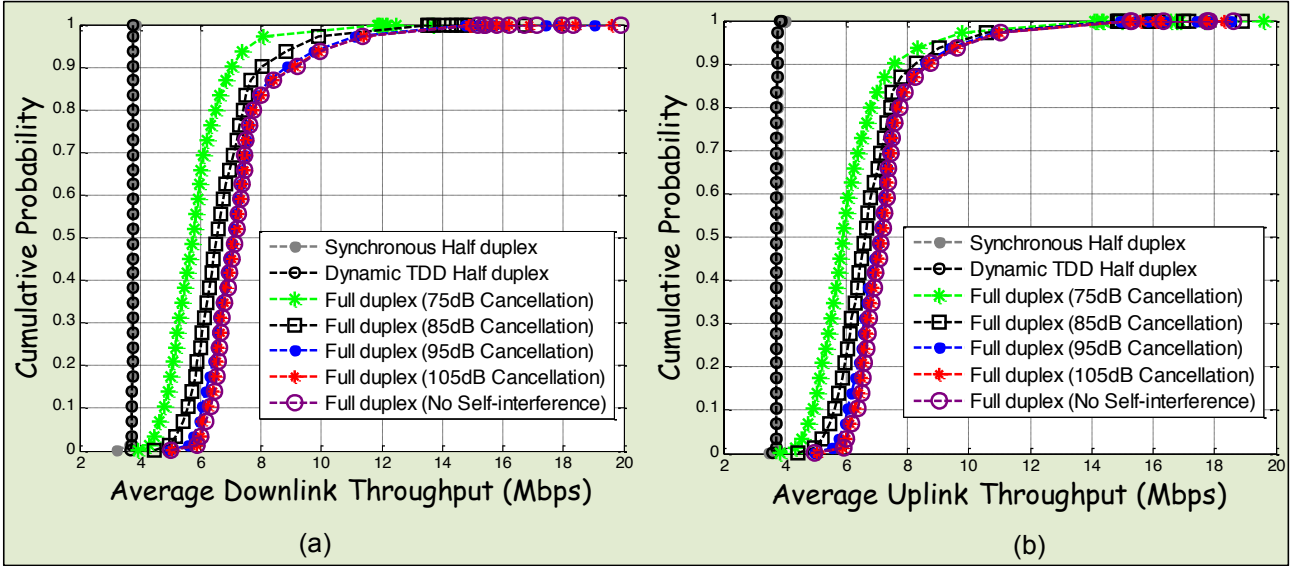


Figure 3. Distribution of average data rates for the half duplex system and full duplex system with different self-interference cancellation capabilities.

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Downlink	(3.74, 4.40)	0.045	0.097	0.227	0.326	0.434
Uplink	(4.91, 4.91)	0.017	0.151	0.734	1.360	1.971

Figure 4. Average energy efficiency (terabits per joule) for downlink and uplink directions.



Figure 5. Average throughput gain and energy efficiency (terabits per joule) with full duplex UEs.

	75 dB Cancellation	85 dB Cancellation	95 dB Cancellation	105 dB Cancellation	No Self-interference
Downlink	44%	72%	91%	95%	96%
Uplink	50%	69%	85%	89%	91%
Downlink	2.02	1.01	0.80	0.75	0.73
Uplink	1.46	2.47	3.23	3.58	3.61

Average Throughput Gain

Average Energy Efficiency (Tbits/Joule)

Figure 6. Average throughput gain and energy efficiency (terabits per joule) with power allocation method that includes a penalty for higher power consumption.