Full Duplex Radios: Are we there yet?

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ABSTRACT

Full duplex communication has been well explored in the past decade, with several physical layer designs proposed for effectively doubling the throughput of mobile devices. However, these systems are far from being well-deployed in the Wi-Fi and cellular applications, where most of the research has been done. In this paper, we investigate some of the fundamental pragmatic challenges in deploying full duplex that explain the reluctance from industry players in deploying this feature in commercial end-user devices and base stations at a large scale. Upon doing so, we identify that the problems lie not quite at the radio layer – but at layers below and above it. At the hardware layer, we find that the power and complexity of IC-implementations of full duplex far exceeds that of other existing technologies that achieve similar throughput gain, such as multi-user MIMO. We further identified how higher-layer cellular and Wi-Fi traffic patterns and MAC protocols are fundamentally ill-suited to the full duplex paradigm. We report empirical analysis from the power consumption of an IC-implementation of a full duplex cancellation circuit, demonstrating that full duplex cancellation circuitry would consume at least 57% more power than a MIMO system achieving identical throughput gains. We also show how current traffic patterns reduce the benefits of full duplex to 1.25× instead of the expected 2×.

CCS CONCEPTS

• **Networks → Network performance analysis**; *Network components*; • **Theory of computation → Circuit complexity**; • **Hardware → Integrated circuits**; **Circuits power issues**.

KEYWORDS

Full Duplex; self-interference cancellation; Integrated Circuit implementations; MIMO

ACM Reference Format:
Vaibhav Singh, Akshay Gadre, and Swarun Kumar. 2020. Full Duplex Radios: Are we there yet?. In *Proceedings of the 19th ACM Workshop on Hot Topics in Networks (HotNets '20), November 4–6, 2020, Virtual Event, USA.* ACM, New York, NY, USA, 8 pages. https://doi.org/10.1145/3422604.3425925

1 INTRODUCTION

Full duplex communication in wireless networks has seen a lot of interest in recent decades, especially from academia with major thrust in system design and implementation. Full-duplex communication can effectively double the throughput of wireless communication systems by removing the self interference. Indeed recent work has shown that it can provide this benefit for various technologies such as cellular and Wi-Fi [7, 30, 69]. Despite the clear benefits of this technology, there has been very limited adoption from industry to incorporate it into commodity cellular and WiFi devices. In spite of the major gains in throughput of full duplex systems, there are some practical problems that prevent it from widespread deployment unlike advances such as multi-user MIMO that are ubiquitous. In this paper, we investigate the source of these problems and address the broader question of whether adopting full duplex in the field, particularly at the last mile, is prudent given the need to keep end-user devices low-cost, low-power and low in complexity.

There has been much work in developing full duplex communication systems for WiFi and cellular by cancelling the self-interference leaking from the transmitter into its own receiver. Many of these systems also demonstrate the ability to work in consonance with traditional MIMO systems to further improve the throughput of these technologies. Past work has focused on designing innovative self interference cancellation techniques at antenna, analog and digital domains [7, 13, 16, 17, 20, 27, 41]. Recent work [19, 23, 45] has also discussed the impact of enabling full duplex functionality on the MAC and network layers. We believe all these advances are valuable from a research perspective in demonstrating new capabilities for radios and have applications far beyond Wi-Fi or cellular communication (e.g. sensing). However, in this paper, we seek to address a far more narrow, but important question pertaining to full-duplex Wi-Fi and cellular communication that spurred the initial excitement around full duplex radios, when they were first proposed.

In this paper, we ask – why is it that, despite the immense benefits provided, adoption of the full duplex technology for communication in commodity wireless devices has been slow. In our search for the answer, we had to look outside of the radio layer, where much of full-duplex research has been focused. Specifically, we identify practical challenges at the layers both below and above the radio layer that impede the proliferation of full-duplex. First, at the hardware layer, we show how full-duplex cancellation circuitry is extremely energy hungry and challenging to fit compactly in a small form factor, ruling it out for most end-user devices in Wi-Fi or cellular. We show that even an IC-implementation of a full-duplex cancellation circuit would increase smartphone power consumption by at least 40%. Second, we observe that higher-layer traffic patterns in modern cellular and Wi-Fi are highly asymmetric, with traffic that is much more loaded on the downlink versus the uplink. This disadvantages full-duplex, whose gains are maximum only when traffic demands

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HotNets '20, November 4–6, 2020, Virtual Event, USA

ACM ISBN 978-1-4503-8145-1/20/11.
https://doi.org/10.1145/3422604.3425925

in both directions are largely equal. We expand on these reasons below:

Complexity of client at the hardware layer: We first ask: "Is the end user device ready for full-duplex operation?". It is obvious that the increased complexity required for self-interference cancellation will not only require new cancellation techniques but it will also need much more complicated circuitry to be installed in the devices. While bulky base stations and access points might have the resources to implement this complex circuitry, it is unreasonable to achieve it within small form factor devices (phones, etc) given the power and space constraints [10, 70, 80]. This is perhaps the fundamental problem that prevents full duplex operation on end user devices currently. In Sec. 3, we analytically characterize the amount of power (and space) required to implement a self-interference cancellation integrated circuit, based on recent works [58, 89], and compare it with that required to implement a MIMO circuit offering similar throughput gain using similar components. Our empirical evaluation on a simple single stream full duplex node shows that a full duplex system consumes 1.57× more power compared to a MIMO system providing similar throughput. We find that this problem materializes regardless of the approach used to achieve cancellation, whether by time-domain methods, frequency domain methods or the use of a circulator. Indeed, the high-bar for required analog cancellation in full duplex systems (~40-50 dB in analog) appears to be the culprit, as well as the need to mitigate signal multipath. To put these energy overheads in context, we estimate that regardless of approach, full duplex cancellation circuitry would consume 40% extra power in a smartphone in active RF mode.

Compatibility with Traffic Patterns at Higher Layers: A second problem that full duplex faces stems from the asymmetry of the traffic between the uplink and downlink at the higher layers. Specifically, full duplex requires symmetric demands for traffic along both directions of a bi-directional link to ensure concurrent transmissions and therefore maximum (2×) gain. However, traditional demand in Wi-Fi and cellular systems is significantly skewed towards the downlink. While some applications such as voice and video calls require equal demands, these account for a modest portion of current cellular and WiFi traffic [31, 62, 83]. In effect, this dichotomy reduces the maximum possible gain on a typical cellular or Wi-Fi network to about 25%, much lower than the 100% gain possible with ideal bidirectional full duplex.

Another challenge with full duplex deployment in the Wi-Fi context is the extra requirement of synchronization between the simultaneous transmission at the uplink and downlink. Specifically, full duplex designs require accurate estimates of the channels from the preambles transmitted at both the uplink and downlink to perform self-interference cancellation. However, these preambles cannot be transmitted concurrently and must be estimated for every single packet. This leads to an additional synchronization overhead that is at odds with protocols that lack synchronization at the MAC-layer such as Wi-Fi. Further, even in protocols that do have global synchronization such as cellular, this means that traffic on the uplink and downlink needs to be synchronized per-packet to take maximum advantage of full duplex, which will lead to latency and scheduling overheads.

Important Caveats: While the above highlight some of the fundamental challenges preventing widespread full-duplex deployment for communication at the last mile, we would like to highlight the immense research value of full duplex in other contexts such as RADAR sensing [4, 42, 43, 74] and RF backscatter [48, 49, 51, 82]. We further add that some of the full duplex's weaknesses such as client-complexity at the last mile may not be as important elsewhere in the network (e.g. relays in the back-end) – a topic that we also discuss. While some of the challenges mentioned above like circuit complexity can be overcome with advancement in technology over time, it should be noted that other challenges like asymmetric traffic patterns in Wi-Fi and cellular are unlikely to change in the long term.

Contributions: This paper explores the fundamental challenges in deploying full duplex in the last-mile in Wi-Fi and cellular networks in layers outside of the usual radio layer – the hardware and higher layers. Our contributions include:

- An analysis of the significant power, space and complexity bottlenecks of selected integrated circuit implementations of full-duplex on end-user devices.
- A study of expected performance-gains of full-duplex in cellular and Wi-Fi deployments as well as an analysis of the synchronization overhead of full duplex.
- A comparative study of the power consumption of three IC-based representative full duplex techniques.

2 RELATED WORK

Past work in full duplex design delving into deployment and complexity analysis are summarized below:

Full Duplex PHY and MAC: Past work on Full Duplex PHY and MAC layers are summarised in [23, 39]. At the RFIC design front, [24, 32, 38, 75, 85, 89, 90] have attempted to make full duplex suitable for small form factor devices, however these designs either yield low self interference cancellation or are bulky and power consuming. Moreover, most of these have been left at nascent stages after proof of concept verification without integrating them into user devices which could provide more insights into integration overheads. At the MAC layer, there have been some designs to overcome the internode interference in full duplex networks via Non Orthogonal Multiple Access techniques [15, 25, 55, 56, 78, 88], using power or code allocation for different users, however these require complicated processing on top of the already complicated full duplex self interference cancellation circuit. Other approaches [60, 63, 66, 71, 76] have tried to induce artificial symmetry in the network traffic patterns using interference management and scheduling techniques, but their implementation is limited to backhaul and relay-type multihop networks.

Full Duplex Vs MIMO: Recently, there has been some focus on combining as well as contrasting full duplex gains with MIMO due to the similar nature of throughput gains they advertise. [6] demonstrated how full duplex gains scale with MIMO for a 3×3 antenna Wi-Fi systems as well as highlighted the subtle differences from just extending the simple SISO full duplex system approach on a PCB. [9, 18, 57] presented initial designs of MIMO full duplex capable ICs but the end-to-end evaluation of the performance is limited. [3, 68] use clever beamforming and nulling techniques to enable Full Duplex MIMO operation for isolating the TX and RX streams for Massive MIMO base stations, however they sacrifice some of the spatial multiplexing gains while doing so. [77, 91] show theoretical models for achievable capacity in MIMO uplink-downlink networks and propose switching thresholds for moving from full duplex to half duplex operation or vice-versa based on the network configuration based on achievable sum-rates. To our knowledge, this paper is the first to explore a broader end-to-end cost-benefit analysis of full-duplex in the context of alternatives such as MIMO.

3 COMPLEXITY AND POWER

In this section, we study an important consideration that emerges when full-duplex is deployed in the link between the base station and client – the power and space constraints of a mobile device.

Take-Away #1: An end-to-end full duplex IC on phones incurs an additional energy overhead of 57% vs. a MIMO system with identical throughput on a 2-node link.

3.1 Full Duplex is Power Hungry

One of the key bottlenecks in accelerating deployment of any wireless technology is the availability of power and compute-efficient integrated circuits (ICs). Like any other nascent technology, much of the early work on full duplex [6, 7] focused more on perfecting the capability by developing custom bulky PCBs providing great insights on various approaches for self-interference cancellation. Over the last decade, as the technology has been progressively perfected, there has been a natural shift in focus toward actually implementing the self-interference cancellation RF circuit on a much more compact IC [14, 24, 32, 54, 58, 89, 90], compatible with a small-sized mobile device. While tremendous leaps have been achieved via research in solid state devices and RFIC design, there remains an unexplored bottleneck for such devices - power consumption of the digital cancellation pipeline. These digital pipelines are typically bulky signal generators and mounting stages. While the analog cancellation has been optimized for power, the total power consumption of the mobile device also depends on the peripheral feeding circuitry for the analog cancellation along with the digital processing to enable that circuit. Typically, this has been either implemented on a separate chip (or a combination of chips). As of today, these components remain too power-hungry and can consume around 40% additional power in a mobile phone (typically active mode WiFi/cellular operations on mobile consume 800-900 mW of power [10]).

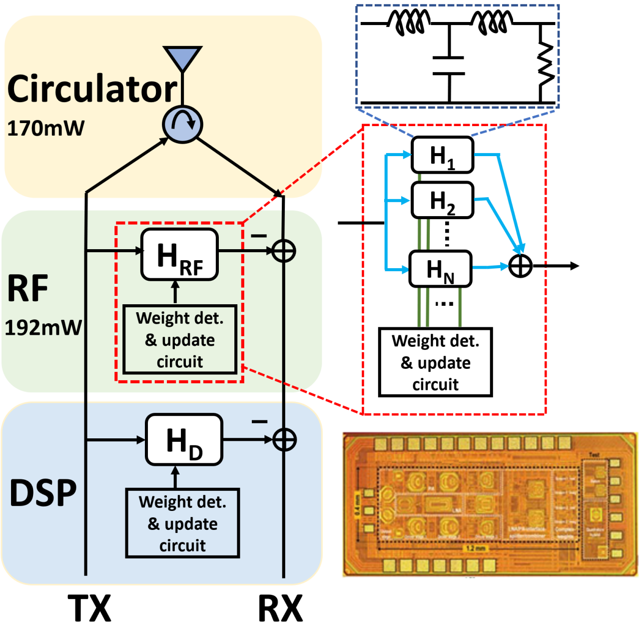

Figure 1: Simplified schematic of full duplex transceiver chain with N-tap RF Self interference canceller. Bottom right shows the single channel self-interference cancellation Full Duplex IC [58]

To understand where this extra power consumption comes in, it is critical to understand how full-duplex systems work. The main task in any full-duplex system is to cancel your own transmitters' signal at the receiver antenna. This signal can traverse multiple paths to reach the receive chain from the transmit chain. Much of this extra power consumption in a full-duplex system comes from the overheads required to cancel this signal across the various paths. Next, we show how three popular cancellation approaches in full-duplex all incur significant energy overhead.

Circulator Approach: A typical radio antenna is a passive device which does not consume much energy. While there have been approaches that use multiple antennas for each RF chain in full-duplex, it is naturally preferred to use a single antenna for the transmit and receive chains to ensure that the system can fit in a small form factor (specially if additional antennas are used for MIMO gain). Most works that operate using a single antenna use a circulator. This circulator is an extremely bulky and expensive device which provides significant isolation between the transmit and receive chains. If one uses a passive circulator operating using a ferrite material, it remains too bulky and infeasible to implement on an IC. However, recent work has developed active circulators optimized for IC implementations [28, 40, 59, 65]. Unfortunately, being an active component, even the best (high isolation, low loss and low noise figure) of these IC implementations [59] require 170 mW of power (∼19% increase in active RF power consumption). Another problem is that this power consumption scales linearly with the number of transmit-receive chain pairs in full-duplex MIMO systems.

Further, there is additional analog circuitry required to cancel a significant amount of remaining self-interference before it reaches the digital frontend (to avoid the capture effect). This is typically achieved by building self-interference cancellation paths from the transmit to receive chain. These approaches for self-interference

full duplex IC Design	1-tap	4-tap	%power
Circulator [59]	170	170	19%
Time domain [58]	37	148	16%
Frequency domain [89]	48	192	21%

Table 1: Power (mW) and percentage increase in active power requirement from 900 mW total power consumption of smartphone [10]

cancellation either operate in the time domain or the frequency domain.

Time-Domain Approach: In time-domain, these cancellation paths are typically implemented as second-order filters with tunable parameters. Fig. 1 shows the general workflow of an N-tap RF cancellation transceiver chain whose single-tap RFIC is implemented in recent work [58]. It is a compact IC occupying an area of 0.48 mm^2 and consuming a power of 37 mW. However, remember that we need to cancel multiple paths to achieve relevant amount of self-interference cancellation at WiFi and cellular frequencies. However, this would require a more complex circuitry that can cancel these paths, naturally consuming more power at the mobile device.

To understand how increasing the number of self-interference cancellation channel taps in the RF chain affects the complexity, let us take an example of a single-antenna full-duplex circuit requiring N taps to yield a decent amount of analog cancellation(40-50 dB). We also assume power P required and space S occupied for the corresponding single tap self-interference cancellation circuit. This would require N distinct implementations of the configurable filters, which in turn mean increase in the power requirement and space occupied to $N \times P$ and $N \times S$. However, this does not capture the complete picture as we still need to account for the peripheral circuitry required for feeding the N delayed versions of the transmit signal into the circuit as well as compute the N configurations. It is fundamentally difficult to implement these delayed lines in IC because of the large length required for achieving even nanoseconds delay [6, 13]. Thus, it is generally desirable to generate these delayed signal copies in digital and then feed it to the IC, however this incurs additional complexity of the feeding network. Simply put, the total power consumption incurred at the analog stage is more than the sum of its components due to these additional overheads. Based on recently developed state-of-the-art IC designs [58], we estimate that a cancellation circuit using 4 taps would lead to additional power consumption of roughly 148 mW which is around 16% increase in the total power consumption of a mobile device excluding the additional power required for the peripheral circuitry required for self interference channel estimation, update and the feeding network.

Frequency-Domain Approach: Frequency-domain equalization approaches [13, 89] have been suggested to overcome the limitations of time-domain delay line based approaches in IC implementations. These approaches try to estimate the self interference channel taps in the frequency domain and these taps are implemented on the IC using a cascade of bandpass filters. While this approach overcomes the problem of long delay lines, it still suffers the problem of low achievable self-interference cancellation with low number of frequency domain channel taps. For instance, [89] requires at least 4 taps to achieve an analog self-interference cancellation of around 52 dB, with a single tap implementation requiring 44 mW power and 4.8 mm^2 area. As analyzed earlier, these power and area numbers are expected to scale linearly with increasing number of taps.

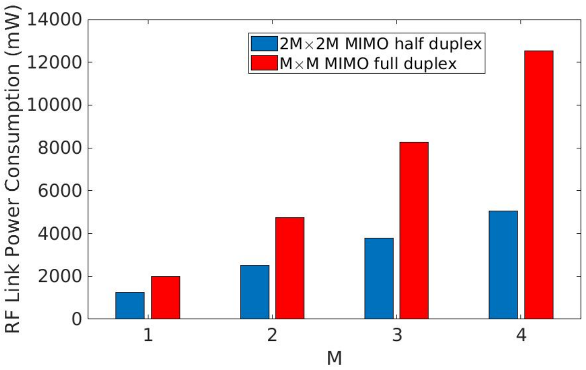

Figure 2: Power consumption for half duplex MIMO and full duplex MIMO links yielding same throughput computed from power of individual technologies in [59, 84, 89]

3.2 Can MIMO Full-Duplex give scalable gains?

While theoretical analysis of throughput gains achieved upon combining full-duplex in MIMO settings has been well characterized in [77, 91], enabling implementations in IC for extending full-duplex to multiple antennas is even more complicated. In such a M×M antenna system, at each receive chain, we will need to cancel N copies from each of the M transmit chains. Thus, the total circuit would easily extend to M^2NP power and M^2NS area consumption without even considering the extraneous amount of peripheral circuitry required to enable such a system. This will incur significant strain on the power consumption of the mobile device even for a small value of N. While some systems [6] have proposed reducing the number of cancellation chains, work on implementing them in IC has been limited.

Comparing Energy Requirements: A natural question then arises : "If I want to increase my throughput, should I use MIMO or MIMO along with full-duplex to be more power-efficient?" We endeavor to correctly characterize the cost of achieving the gains in throughput for both of the above configurations. We compute the power consumption for a full duplex configuration based on the power consumption of the individual components (appropriately scaled for technology), namely, circulator [59], frequency domain cancellation [89] and MIMO [84]. We use these as representative of state of the art since all of them operate in similar frequency bands, have good performance in terms of self interference cancellation and power to ensure a fair comparison. We then analyze the two configurations in Fig.2 with increasing number of transceiver chains(M) to identify which approach provides better power efficiency. Our results demonstrate that to achieve the same throughput, 1×1 full-duplex requires 57% more energy than näive

2×2 MIMO. As the power overhead of self-interference cancellation increases quadratically, this trend worsens. Thus, full-duplex and full-duplex MIMO are strictly and significantly inferior to MIMO in terms of energy cost under identical throughput gain.

While we acknowledge that the power numbers of components might vary slightly with precise implementation details in prior art, the RF link power consumption for self-interference cancellation still scales quadratically for full duplex MIMO over MIMO for achieving similar throughput. This trend remains irrespective of improvement in technology.

Comparing Space Requirements: One may think that MIMO requires additional antenna space on a mobile device compared to full duplex. However, commercial phones have already achieved 4×4 MIMO [35], through innovative antenna placement. The need for additional space for MIMO antennas therefore does not sufficiently tilt the needle in favor of full-duplex.

In summary, our take-away message is that regardless of approach, today full-duplex cancellation has a significant end-to-end energy cost. Indeed, while there is no commercial end-to-end implementation of full-duplex on a mobile device (perhaps for this very reason), our analysis aggregated from various academic literature in this space provides a perspective on the fundamental energy bottlenecks in cancellation, regardless of approach. We also caveat our take-away with a rider that future innovations in circuit design could lead to energy improvements, although we would need significant end-to-end improvement to witness feasible and energy-efficient full duplex for mobile devices. These IC design innovations will in turn determine the monetary cost of enabling full-duplex circuits in end user devices which will be implementation specific and hence, beyond the scope of this paper.

4 TRAFFIC PATTERNS AND MAC

In this section, we study the feasibility of full-duplex in traditional Wi-Fi and cellular networks based on their traffic patterns as well as considerations for the higher layers.

Take-Away #2: Asymmetric traffic on the downlink and uplink in Wi-Fi and cellular, causes the gain of full-duplex to fall to 1.25× versus the expected 2×.

4.1 Network Layer Traffic Asymmetry

A full-duplex system achieves maximum gain only when there is sufficient data to send simultaneously on the uplink and downlink. This means that if data traffic is asymmetric in some way, for instance, if downlink traffic from a base station to a client far exceeds the uplink traffic in reverse, the gains of full-duplex are minimal. Contrast this with other techniques such as MIMO or multi-user MIMO, whose benefits can be leveraged across uplink and downlink asymmetrically. While some applications such as VoIP and Video conferencing do have relatively symmetric traffic patterns, recent surveys in bandwidth usage by consumers of both cellular and WiFi show significant downlink-uplink asymmetry.

For example, [31] shows that in a conference environment of 45 WiFi clients over 83% of traffic is downlink. A similar study conducted during SIGCOMM 2004 [67] also shows 80% of the WiFi traffic to be downlink. Traffic characterization research [61, 62, 83] in cellular networks demonstrates similar trends with 60-80% of cellular consumption being downlink. Further, the trend from 2G (60%) to 3G (69.69%) and 3G (69.69%) to 4G (87.5%) seems to show that this asymmetry is likely to worsen for commodity mobile devices in the future generations. This means, for most applications, the benefits of full-duplex would be very limited unless used for specific applications with symmetric traffic.

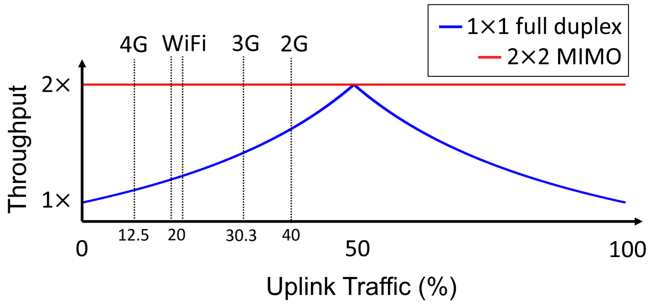

Figure 3: Effective throughput benefits of full duplex are significantly worse than expected due to asymmetry in network traffic

Fig.3 shows the expected gain in throughput of 2×2 MIMO and single antenna full-duplex over half-duplex SISO communication. As expected, the maximum benefits expected by using full-duplex are significantly worse than 2× ranging from 1.67× for 2G to 1.14× for 4G based on just the traffic asymmetry. Note that in practice, this benefit will be worse due to residual self-interference.

4.2 MAC layer Overhead

Beyond traffic asymmetry, another factor that impacts the promised two-fold gain of full-duplex is overhead at the MAC layer. We illustrate this problem by taking the example of two single-antenna full-duplex nodes, although our findings generalize for full-duplex MIMO systems as well.

Synchronization Overhead in Wi-Fi full duplex: The primary source of the overhead at the MAC layer is that, to perform full duplex cancellation, both the base station and client need to synchronize for sending their preambles one-by-one in an interference-free manner. This is required for both the receive chains of the base station and client to measure the channel of their respective transmit chains independently after which they will be able to cancel self-interference and operate in a full-duplex manner. This would require *a priori* synchronization between the nodes to determine these time slots and packet sizes they will be transmitting. This approach will break the random access nature of WiFi where a node can asynchronously wake up and perform CSMA/CA to communicate. Thus, the base station and client need a mechanism to synchronize their data transmissions in time while avoiding collisions for preambles, adding synchronization overhead to otherwise asynchronous systems. This problem is further exacerbated when the number of antennas at each client becomes more than one. This is because longer preambles (one symbol per antenna) would need to be sent in an interference-free manner between base station and client.

Note that full-duplex systems need to estimate self-interference channels on a per-packet basis due to channel dynamics. In other words, full-duplex inherits additional CSMA/CA style overhead in sending preambles as well as time synchronization overhead in sending data. Contrast this with MIMO, where all transmit antennas are on the same physical device and synchronization comes for free.

Compatibility with cellular MAC: Due to the inherent time-synchronization in cellular networks owing to its centralized architecture (courtesy the base station), one may think full duplex will be easy to implement in cellular. Yet there are two major challenges in this regard. First, many countries such as the US and India use FDD-based or hybrid (with TDD) models where clients are configured to communicate at a separate frequency. Hence, implementing full duplex in these countries will require major policy and infrastructure change. Second, full duplex introduces additional latency in ensuring that concurrent traffic is available on both the uplink and downlink prior to transmission, which impacts latency-sensitive applications such as voice and video streaming.

In summary, the synchronization and compatibility issues pose some fundamental issues at the MAC layer in full-duplex networks despite its potential to alleviate the hidden terminal problem and boost end-to-end throughput in multinode networks as shown in [12, 45, 46, 86].

5 DISCUSSION

While the prior sections have primarily focused on Wi-Fi and cellular, and the last-mile link between the base station and the clients, there are various other applications where full-duplex has already been deployed.

Full-Duplex in Backscatter and Sensing: Despite the aforementioned challenges, there are many places where full-duplex is already used to leverage its many attractive properties. The first property that is typically exploited is the ability of full duplex systems' transmit chain to be synchronized by the receive chain. This ability is exploited in the vast amount of related work in backscatter networks[5, 34, 47, 79], where the signal that is incident on a passive/active backscatter tag is reflected with either a phase, amplitude or frequency shift with known phase properties. This enables base stations to detect these feeble signals added to the original signal at another base station with minimal overhead.

Another attractive property of full-duplex systems is the ability to completely remove the direct path interference between antenna. This enables various wireless RADARs such as mmWave RADARs, SAR satellites to identify the reflections from objects around a multi-antenna transceiver. SAR satellites have been extensively used for topographical applications spanning agriculture [29, 50, 53], meteorology [8, 52, 73] with several recent satellite launches improving on prior capabilities. Similarly mmWave RADARs are extensively used in autonomous vehicles [22, 33, 72], drones [1, 36] with recent work [64] on leveraging them for sensing.

A place where full-duplex communication really shines though is its ability to act as passive relays[11, 44] providing enabling immense improvement in coverage especially for narrow beam technologies such as visible light communication and mmWave radios. These passive systems either provide additional path for the client to reach the base station or reinstrument the environmental multipath to assist the signals to reach the base station.

Recently there has been some interest towards using some of the self interference cancellation techniques developed for full-duplex communication in the context of Non Orthogonal Multiple Access cellular topologies [2, 21, 81] for cancelling inter-node interference in the near-far scenario. Full-Duplex techniques have also been proposed for defense and security applications [26, 37, 87] where downlink transmit signal from the full duplex base station is used to jam the reception at an eavesdropper trying to sniff the authenticated user uplink signals.

Full-duplex for backhaul relays: A natural question to ask from above is whether full-duplex works really well for providing cellular wireless backhauls. Unfortunately, there are three problems in this regard. First, as mentioned earlier, full-duplex is significantly more power consuming than typical half-duplex communication. This makes it incompatible with the vision of future femtocells where these base stations could even be deployed in street lights providing connectivity. Further, even backhaul relays that operate elsewhere in the cellular network are impacted by the significant power requirements of full-duplex, which increases the cost of nodes. Finally, and more critically, there is the issue of traffic asymmetry between traffic along the backhaul meant for the uplink versus downlink, which again reduces the throughput gain of full duplex, especially per unit cost and power. In effect, this motivates the current preference of cellular wireless backhauls towards MIMO or other choice of frequency bands with wider bandwidth, as opposed to opting for complicated and power-hungry full-duplex circuitry.

6 CONCLUSION AND WAY FORWARD

In this paper, we ask: "Are we close to the adoption of full-duplex radios for WiFi and cellular communication?" Our experience in developing full-duplex systems and lessons from end-to-end system analysis lead us to believe full duplex is not there yet. Full duplex is too power-consuming for deployment in mobile devices, and real-world traffic patterns and MAC layer overhead reduce its benefits versus cost.

We do however emphasize that full-duplex continues to remain important and practical for many other systems such as backscatter and RADARs. Further, we believe full-duplex could find applications in certain emerging application contexts and with advancements in circuit design. One such application domain is collaborative sensing for autonomous vehicles where the traffic is much more symmetric and throughput needs are high. Further, active research is being invested in full-duplex ICs that are power-efficient, which may pave the way for improvements across all of the three critical parameters - throughput, power and latency.

Acknowledgements: We are grateful to Professor Fadel Adib from Massachusetts Institute of Technology and Susnata Mondal from Intel for their valuable inputs and discussions. We thank the reviewers and all the members of the WiTech Lab at CMU for their insightful feedback which helped improve this paper. This research was supported in parts by NSF grant 1823235, Kavčić-Moura grant, CyLab Presidential Fellowship and IoT@CyLab.

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