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Virtual Duplex: Scaling Dense WLANs and Eliminating Contention Asymmetry

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***Abstract*—In this paper, we propose "Virtual Duplex," a wireless architecture which, like Frequency Division Duplex (FDD), divides spectrum resources into two sub-bands. However, in contrast to FDD, both bands in Virtual Duplex are physically bi-directional, and transmissions are allocated to the bands according to whether they correspond to download or upload traffic. The "download data channel" carries data originating from the AP and that data's associated reversed-direction acknowledgements, and vice-versa for the "upload data channel." Thus, Virtual Duplex separates upload and download traffic at the link layer so that MAC layer Data-ACK handshakes are allocated into one of the two (physical) independent and asynchronous bi-directional channels. The spectrum division can be equal (as is typical with FDD) or weighted with a configurable bandwidth allocated to each channel to guarantee a spectrum share independent of client density. We show that the logical division and spectrum isolation between upload and download Data-ACK handshakes increases spectral efficiency, eliminates contention asymmetry and provides scalability to traffic asymmetry. Experimental and simulation results demonstrate that Virtual Duplex matches download vs. upload throughput to demand ratio within 1% under any client density and traffic load. This matching capability offers unbounded download gains as congestion increases, minimizing and in some cases eliminating retransmissions and contention time.**

I. INTRODUCTION

Bi-directional or duplex communication can be supported at the physical layer by separating traffic according to direction, e.g., by separating uplink and downlink traffic by frequency or time as in FDD or TDD cellular systems. In contrast, WLAN MAC protocols such as IEEE 802.11 are largely agnostic to physical direction, as access points (APs) and clients contend for the same spectrum resources using the same channel access procedure (backoff, retransmission, etc.) irrespective of whether the transmitter is an AP or a client. In a WLAN, upload traffic is commonly generated by a larger number of nodes (i.e. clients) than download traffic (i.e. APs). Consequently, since 802.11 CSMA targets to provide all nodes (AP or client) with equal medium access probability, the clients create a disproportionate amount of contention yielding *contention asymmetry* between uplink and downlink data traffic. Thus, in a network with N clients, CSMA targets the AP data transmissions to receive only $1/(N+1)^{th}$ of spectrum resources. This problem is aggravated because upload and download traffic demands are different. Server-based multimedia streaming applications (e.g., YouTube, Netflix, Pandora) and many client-server applications such as web browsing yield highly *asymmetric traffic demand* with the vast majority of traffic being transmitted from the server to the client as opposed to vice-versa.

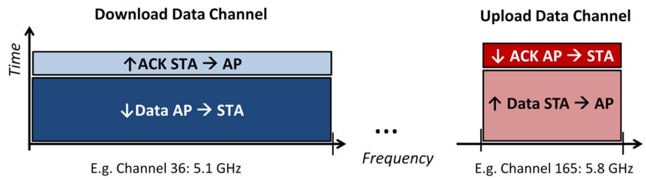

Fig. 1. Virtual Duplex Channel Architecture: two bi-directional physical channels each with a single uni-directional MAC traffic direction with configurable bandwidth allocation.

In this paper, we introduce Virtual Duplex, a wireless architecture that provides spectrum independence between upload and download traffic. We refer to *upload traffic* as both the uplink data transmission from the clients to the AP as well as the associated *reverse-direction* acknowledgements from the AP to the client. In other words, upload and download respectively refer to MAC layer Data-ACK handshakes originating from clients or from APs. In contrast to FDD which provides physical directional isolation, each of the two bands in Virtual Duplex is physically bi-directional, since both data and its associated reversed-direction acknowledgements share a physical channel, as shown in Figure 1. In contrast to *full-duplex*, which seeks to enable each node to transmit and receive at the same time, Virtual Duplex is more general: a Virtual Duplex node may physically transmit on both sub-channels, physically receive on both sub-channels, or transmit on one and receive on the other. Namely, the physical sub-channels of Virtual Duplex operate asynchronously and independently with channelization performed according to the logical division between upload and download.

In particular, we present the following contributions: We first describe the Virtual Duplex architecture and its two key advantages: First, it provides client scaling via spectrum isolation between upload and download traffic. This isolation increases spectral efficiency by eliminating contention asymmetry and providing scalability to traffic asymmetry. Second, Virtual Duplex provides control of resources allocated to upload vs. download via the partition of spectrum resources into two sub-bands. This fixed-resource share contrasts with 802.11-like MAC protocols in which download traffic obtains a resource share that scales inversely with the number of clients. Likewise, schemes that prioritize AP traffic over client traffic via use of reduced contention windows obtain an unpredictable division of upload vs. download throughput, e.g., [1], [2], [3], [4], [5], [6].[1]

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[1] See Section IV for a complete discussion of related work.

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Second, we implement and perform an experimental evaluation of Virtual Duplex. Namely, we build a prototype of Virtual Duplex with software extensions to commodity Wi-Fi hardware. We also implement a two channel Wi-Fi scheme and also use legacy (single-channel) IEEE 802.11 as baselines for comparison. Moreover, we design a simulation platform to study more complex and large-scale scenarios that are not feasible with test hardware.

Our experiments explore both client scaling and spectrum isolation. Ideally, the ratio of download to upload *throughput* is the same as the ratio of download to upload *offered load* or demand. However, high contention between upload and download traffic in legacy systems severely degrades download performance, specially with high client density. Our evaluation demonstrates Virtual Duplex approximates the ideal throughput ratio of 1 (i.e., throughput matches demand) within 1%, even as client density scales. In contrast, in legacy systems with 20 clients, upload obtains 26% more bandwidth than desired. The disproportion between throughput share and offered load of legacy systems grows as the number of clients increase. For example, with 100 clients, download traffic is served only with 10% of the resources in legacy systems. Virtual Duplex's matching capability translates into significant gains over baseline systems. We show that Virtual Duplex's architecture achieves high gains in download throughput, up to 626% for 100 clients. The highest gains are observed in congested scenarios, because baseline download performance rapidly decays with increasing network density, yielding increased relative performance of Virtual Duplex. We show that Virtual Duplex reduces backoff time of all transmissions by 40% to 50%, and up to 86% for downlink traffic. Further, retransmissions are reduced by 23-36%, and downlink retransmissions are completely eliminated in the special case of 1 and 2 in-channel APs within carrier sensing range of each other, as downlink and uplink packets no longer contend with each other. As result, we observe that Virtual Duplex gains are the consequence of isolating upload and download contention for the same spectrum resources.

The rest of this paper is organized as follows. In Section II we present Virtual Duplex design, specifically our channel architecture, configurable bandwidth parameter and medium access. Section III presents Virtual Duplex implementation and evaluation of throughput to load ratio in relation to contention and traffic asymmetry, and the Virtual Duplex gains over baseline systems. Finally, Section IV overviews related works, and Section V concludes the paper.

II. VIRTUAL DUPLEX DESIGN

Virtual Duplex separates upload and download medium access contention by separating the spectrum resources at the link layer and allowing physically bi-directional data-ACK handshakes within the same channel. In this section, we describe how the key features treat asymmetries and reduce medium contention leading to increased spectral efficiency.

A. Channel Architecture

The channel architecture of Virtual Duplex, shown in Figure 1, decouples upload and download medium access by allocating each traffic direction into one of two independent channels: the download data channel and the upload data channel. Virtual Duplex features physical bi-directional communication within each channel to support the complete MAC-layer data-ACK handshake. The download data channel carries MAC-layer data originating from the AP and transmitted to the clients (downlink), with the corresponding ACKs flowing in the opposite direction (uplink). Likewise, the upload data channel transmits data from the clients to the AP (uplink) and the reciprocal ACKs from the AP to clients (downlink). Unlike FDD systems, in Virtual Duplex no generic control messages use the channel, only the ACKs for the data flow traveling in that channel. Thus, Virtual Duplex provides in-channel control feedback that is paired with transmitted data. Through this allocation, the download and upload data traffic *never* compete for the same spectrum resources, allowing simultaneous, asynchronous and independent upload and download MAC layer data-handshakes.

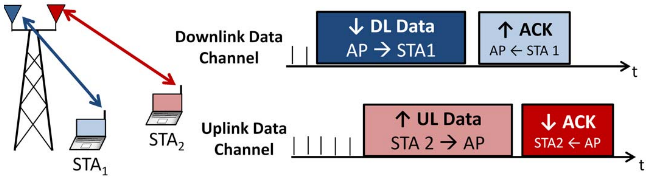

Fig. 2. Bi-directional Data-ACK communication performed individually and asynchronously in each of the download and upload data channels.

Figure 2 demonstrates the MAC level bi-directional communication performed in the frequency independent upload and download data channels. Depicted is an example of a clique-BSS formed by one AP and two stations (STAs), where STA$_1$ receives in the *download data channel* a downlink data packet from the AP and responds with the associated ACK in the same channel. Independently and asynchronously, STA$_2$ transmits an uplink data packet to the AP and receives the related ACK, all in the *upload data channel*.

Bandwidth Resources. Even though Virtual Duplex architecture implements two channels we are not required to double the amount of spectrum resources allocated for legacy devices. Virtual Duplex utilizes the total bandwidth allocated to the system and separates it into two independent configurable-width channels.

Our channel architecture can be implemented with both contiguous bandwidth resources and non-contiguous resources. For contiguous frequency, Virtual Duplex implements the independent download and upload data channels within the total allocated bandwidth but requires a guard band in between these to eliminate co-channel interference. Selection of guard band size has been widely studied [7], [8], [9]; prior work has shown a minimum guard band requirement of 100 KHz to isolate channels, achieved by digital filters [9]. Further exploration of guard band selection is beyond the scope of this paper.

Moreover, the flexibility of Virtual Duplex to implement independent channels with arbitrary and configurable bandwidth resources, leverages the non-contiguous spectrum availability in shared spectrum, like in the TV whitespace (TVWS) band. For example, with non-contiguous 6 MHz channels available in the TVWS band [10], Virtual Duplex can implement the download channel by aggregating 6 MHz channels in one end of the TVWS band and similarly for the upload channel in the opposite end of the band. Because these channels are separated in frequency, Virtual Duplex's download and upload data channels can operate independently without co-channel interference. Figure 1 exemplifies a non-contiguous channel implementation of Virtual Duplex in the 5 GHz band.

Radio Resources. Even though Virtual Duplex implements two independent bi-directional channels, clients can operate with one half-duplex radio and the AP with two radios. We implement Virtual Duplex with two radios at the AP in order to allow the AP to transmit and receive at each channel independently and asynchronously. APs utilize radio resources in the *download* data channel more often because a greater fraction of time is spent transmitting data compared to receiving upload packets and sending corresponding acknowledgments. Clients can use one half-duplex radio and transmit or receive in a single channel at a time, and thus are required to select their operating channel. APs select downlink data transmissions to bypass clients that are transmitting in the upload data channel and thus avoid client *deafness* to downlink transmissions. This is a simple operation, since at any time the AP knows the source of the current upload transmission. Moreover, any STA remains listening to the download data channel while not attempting an upload transmission.

Configurable Bandwidth Allocation. The isolation of upload and download spectrum resources brings a key feature of Virtual Duplex that is a configurable bandwidth division between upload and download traffic. Thus, in the case where demand is asymmetric, Virtual Duplex can adjust the bandwidth division in order to better match performance to demand. The flexibility to adjust the bandwidth division permits the system to be scalable to traffic asymmetry. Virtual Duplex scales to traffic asymmetry, not only by isolating spectrum resources that remove contention asymmetry, but also by allowing the adjustment of bandwidth resources to provide more bandwidth where and when required. Virtual Duplex presents the flexibility to implement existing bandwidth configuration algorithms e.g. [11], [1], [4], [5] and existing traffic estimation techniques e.g. [12], [13], [14], [15]. As the traffic asymmetry between downlink and uplink traffic grows, our system benefits grow by having the flexibility to configure resources to match performance to asymmetric demands.

B. *Virtual Duplex Medium Access Control*

The division of traffic at the link layer permits data traffic to contend *only* with its own traffic direction and allows upload and download MAC to be addressed independently. Virtual Duplex gains and increased spectral efficiency are obtained by having a smaller number of contending nodes per channel, leading to reduced coordination time, collisions and retransmissions.

Upload Medium Access. Virtual Duplex architecture permits only clients to contend for the upload data channel. Thus, upload traffic obtains more medium access opportunities because it does not share the medium with the heavy and continuous download traffic. Moreover, the removal of contention with download data, leads to small scale diversity in the traffic pattern of the upload data channel (only bursty uplink traffic), reducing the probability of collisions with hidden terminals. Furthermore, in the case of hidden terminals Virtual Duplex performance degradation caused by collisions can only affect the upload data channel and can be solved by the implementation of any existing in-channel hidden terminal MAC protocol. The benefit our system brings to the applied hidden terminal solution is that the solution's overhead will only affect the performance of the channel it is applied to.

Download Medium Access. Virtual Duplex ensures that AP's do not contend with clients, only with in-range same channel APs, thus contention is still necessary. To obtain the best spectrum utilization, contention window may be tuned to the number of in-channel APs. For example, in the case when only 1 AP is operating in the download data channel, due to frequency planning, contention and collisions are eliminated, allowing the downlink data channel to approximate full channel utilization with back-to-back data-ack transmissions.

Flexibility for alternative MAC. Virtual Duplex presents the flexibility to separately address upload and download resource allocation. This feature permits to independently address any medium access issue found in either channel, through the implementation of an in-channel solution that will only be applied where required. Virtual Duplex provides the base channel architecture to which we apply a 802.11 CSMA basic access. However, in this paper we do not propose solutions to problems that arise in either uplink and downlink traffic. Instead, we introduce a system that isolates uplink and downlink issues, allowing the system designer to separately address the problems of each channel.

Legacy Co-existence and Channel Access under Multiple APs. Virtual Duplex utilizes 802.11 basic access in each of its channels, thus legacy compatibility exists as long as the spectrum resource allocation between legacy devices and Virtual Duplex devices is coordinated. When both Virtual Duplex and legacy devices operate under a Virtual Duplex AP, the AP can allocate legacy devices in one of the two channels. The AP selects in which of the two channels a legacy device belongs given its traffic load, i.e. low and bursty in upload data channel or heavy and contiguous in download data channel. In the case where legacy and Virtual Duplex devices use the same spectrum resources but different BSS, these encounter the co-existence issue of partial spectrum overlap. This issue is experienced by uncoordinated in-channel APs and can be solved as explained below.

When multiple APs operate in the same frequency resources and have overlapping coverage, the APs should coordinate the spectrum division between upload and download channels, as considered in our implementation. However, if the APs operate independently with overlapping coverage, an uncoordinated bandwidth division will create an interference region between the upload and download channels. This case yields a common spectrum coordination issue of unlicensed bands, as encountered by 802.11 systems with diverse channel bandwidths (e.g. 802.11ac with channel bandwidths from 20-160 MHz) and non-orthogonal channels. WLANs implement simple heuristics to search for non-congested channels [16], [17]. Virtual Duplex APs can detect if a different bandwidth division is being utilized by an uncoordinated in-channel AP by analyzing the signals received at its two radio resources, for the upload and download data channels. Once detected the uncoordinated AP can move to a free channel or coordinate the bandwidth split. Another solution to partial overlapping spectrum is to introduce primary and secondary sub-channels as described in 802.11ac [18] [2]. The primary sub-channel in each of the upload and download channels can be used for carrier sensing, to guarantee no interference between the channels of uncoordinated APs. To achieve no interference among uncoordinated APs, the primary sub-channel must be established as the minimum bandwidth permitted for the upload and download channels.

III. VIRTUAL DUPLEX IMPLEMENTATION AND EVALUATION

In this section, we first present the implementation of Virtual Duplex. Further, we explore through experiments and simulations the performance impact of contention and traffic asymmetry. Lastly, we study the effect of Virtual Duplex's bandwidth division parameter on performance matching and explore the source of the gains of our system.

A. Virtual Duplex Implementation

We implement a Virtual Duplex prototype on a commodity Wi-Fi platform as well as on the NS-2 simulator. As baselines for comparison we implement a two channel Wi-Fi scheme representing a two channel configuration of WiFi-NC [9] and use IEEE 802.11a [19] on both platforms. In particular, 802.11 uses a full 20 Mhz channel, WiFi-NC nodes split traffic evenly among two equal 10 MHz channels that are fully bi-directional instantiations of 802.11 and Virtual Duplex implements two variable width sub-channels within the 20 MHz.

Experimental Platform. Our experimental platform runs Debian Linux with Atheros wireless chipset version AR5413 supporting 802.11a/b/g and utilizing an ath5k wireless driver. We utilize the dbii F-50 pro off-the shelf miniPCI Wi-Fi cards which operate in the 5 GHz band. In order to support 5/10/20 MHz channels (available commodity hardware bandwidth granularity) we implement a modified version of the ath5k driver. We target to maintain an equivalent spectral efficiency across the channels by reducing the transmit power (-3 dBm for every bandwidth division) in relation to the bandwidth size and noise level. Specifically, we set the transmit power to 22 dBm for a 20 MHz channel and reduce transmit power by 3 dBm for every bandwidth division.

Testbed Setup: We conduct our experiments with a five node indoor testbed set in a BSS topology where 4 clients communicate with a single AP. All nodes are in carrier sensing range of each other and present no mobility. Virtual Duplex operates in 5/10/20 MHz channels, the 802.11a protocol operates under a 20 MHz channel and WiFi-NC with two 10 MHz channels without co-channel interference. Our system utilizes combinations of these bandwidths (5/10/20 MHz) for load asymmetries of 0.5, 1, 2 and 4 and is only compared to baseline systems when total bandwidth is equal in all systems. Virtual Duplex's download and upload channels are positioned at opposite ends of the 5 GHz band. In all three systems the total offered load of uplink and downlink data traffic saturates the channel, meaning systems operate under backlogged conditions.

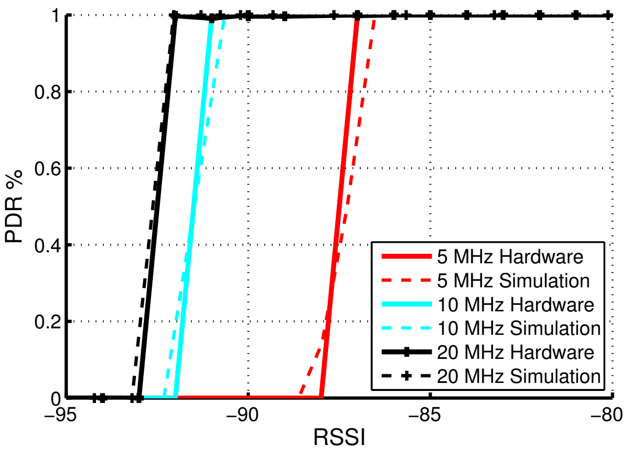

Fig. 3. Packet Delivery Ratio (PDR) comparison between NS-2 simulation and commodity hardware.

Simulation Platform. We implement Virtual Duplex, 802.11a and WiFi-NC on the network simulator NS-2. The NS-2 simulator is modified to allow multiple interfaces and simultaneous multi-channel transmissions to support WiFi-NC and Virtual Duplex.

Calibration: We calibrate the simulation parameters with over-the-air experiments as follows. We perform overnight experiments with no fading and utilize 5 GHz interference-free channels, with non-line-of-sight transmissions. We select the log-normal shadowing model in NS-2 to represent this environment. Figure 3 depicts both experimental and simulation platforms achieve the same Packet Delivery Ratio (PDR) at different received signal strengths. To achieve this, we modified channel path-loss parameters in the NS-2 simulator and identified bandwidth-dependent parameters that were tuned based on the specifications of the IEEE 802.11 Table 18-17 [19].

Simulation Setup: We implement BSS topologies with high client densities, where all nodes are in carrier sensing range, to represent congested WLANs and contention asymmetry. Simulations follow 802.11a parameters [19], carefully adapted for any bandwidth selection. Traffic asymmetry is varied across evaluations, however full channel congestion is maintained. Uplink traffic is equally spread among the number of stations in the network and nodes perform UDP transmissions with constant bit rates and packet size of 1500 B.

B. Throughput Ratio and Load Ratio

Ideally, the ratio of download to upload *throughput* is the same as the ratio of download to upload *offered load*. We utilize the ratio of these two values (ideally 1) as a key metric for performance evaluation. Namely, a throughput ratio to load ratio of 1 corresponds to providing throughput that is directly proportional to demand. In this section we evaluate the impact of contention and traffic asymmetry on the relationship between throughput ratio and load ratio.

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[2] Detailed explanation of 802.11ac channelization techniques can be found at [18]

Impact of Contention Asymmetry. Medium congestion (attempts to access the medium, collisions, etc.) increases as the number of backlogged clients increase. This can yield contention asymmetry in which the many clients provide disproportionate contention compared to the single AP. This in turn can yield a greater probability for a client to gain access to the medium rather than the AP. Here we evaluate the impact of contention asymmetry caused by client density, as measured by the throughput to load ratio.

Setup: We select an upload to download symmetric load, in which download and upload traffic demand is identical, because it presents the highest medium access congestion. Results for asymmetric loads can be found at [20]. Through simulations, we evaluate topologies with 2 coordinated in-channel APs (equal bandwidth division) to introduce a higher downlink data contention to counteract the increasing uplink data contention. To study congested WLANs, the scenario intended for Virtual Duplex, we vary the total number of clients between 20 to 100 and divide these equally across the 2 APs. All three protocols utilize the same total bandwidth. Medium access parameters (SIFS, CW, etc.) follow the 802.11a standard and are equal for all nodes in all systems. Virtual Duplex adapts the download to upload bandwidth ratio based on the network's traffic load and client density.

Results: We measure the throughput for both download and upload traffic, the resulting throughput ratio (DL/UL) to load ratio (DL/UL) is depicted on the y-axis of Figure 4. Any value above 1 on the y-axis indicates that more throughput is given to the download traffic than demanded, whereas download traffic is underserved when the value is below 1. Figure 4 indicates that download performance severely degrades with increasing client density for both 802.11 and WiFi-NC. Even in a network with 20 clients, download traffic is significantly underserved due to upload traffic repeatedly winning contention and utilizing approximately 26% more bandwidth than desired, this corresponds to a value of 0.3 DL/UL throughput ratio (23.4/76.6 vs. 50/50). This situation aggravates as client density increases, for example in the case of 100 clients baseline systems provide a throughput ratio (DL/UL) of 0.1 (9.5/90.5 vs. 50/50), meaning upload traffic is using over 40% of download's intended throughput. In contrast, Virtual Duplex is able to approximate ideal throughput ratio within 1% in all network densities due to upload and download performance isolation. Even though WiFi-NC provides a second contention domain by splitting the band, it does not remove upload to download contention for the same medium, and consequently has a dependency between upload and download performance.

Over-the-Air Evaluation: We perform a small-scale analysis on our experimental platform to verify the hypothesis that contention asymmetry of large-scale scenarios is the reason for unmatched throughput ratio. In the case of small-scale scenarios, upload and download medium contention is approximately symmetric, therefore we expect a near ideal throughput ratio for all systems. We evaluate all systems under a symmetric load with various topologies formed by 1 AP with 2 to 4 clients. As expected, Table I indicates that all three systems achieve ideal throughput to load ratio within 3%. This result supports our claim that contention between upload and download traffic for the same resources is the bottleneck of shared band systems at high client densities.

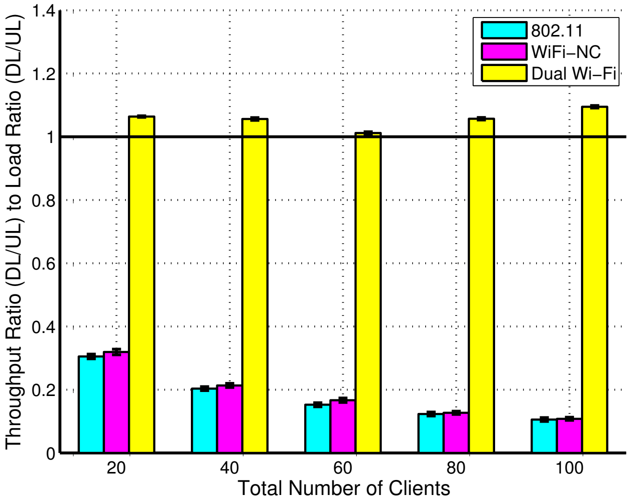


Fig. 4. Throughput ratio (DL/UL) to load ratio (DL/UL) with symmetric load for topologies with 2 APs and 20-100 clients. Note that Virtual Duplex approximates ideal ratio (value of 1) for all client densities.

TABLE I. SMALL-SCALE EXPERIMENTAL EVALUATION OF THROUGHPUT TO LOAD RATIO (DL/UL).

Clients:	2	3	4
Virtual Duplex	0.968 (± 0.036)	1.101 (± 0.065)	1.054 (± 0.013)
802.11	0.991 (± 0.003)	0.991 (± 0.003)	1.027 (± 0.017)
WiFi-NC	0.992 (± 0.004)	1.015 (± 0.012)	1.039 (± 0.018)

Impact of Traffic Load Asymmetry. In this experiment, we analyze the impact of traffic asymmetry (difference between download and upload offered load) on network performance, as measured by the throughput to load ratio.

Setup: For this experiment we fix the number of clients to 20 to represent a WLAN scenario. All clients communicate with a single AP and are within carrier sensing range of each other. For all experiments, the aggregate load is fixed to saturation, and the ratio of the downlink load to the uplink load is varied and depicted on the x-axis of Figure 5. For each of the 3 systems (802.11, Virtual Duplex and WiFi-NC), we measure the corresponding throughput for both download and upload traffic. The resulting throughput ratio to load ratio is depicted on the y-axis of Figure 5.

Results: First, we observe in Figure 5 Virtual Duplex achieves the closest to the ideal ratio (value of 1) under any load asymmetry, matching the throughput ratio within 1% of the demand ratio. In contrast, both 802.11 and WiFi-NC systems fail to equalize throughput ratio and load ratio. For example, when the demand for download and upload traffic is identical, (corresponding to a value of 1 on the x-axis) the y-axis depicts a value of approximately 0.28 for both 802.11 and WiFi-NC. This corresponds to a DL/UL throughput ratio of 22.4/77.6 vs. 50.98/49.02 (DL/UL) from Virtual Duplex, <1% away from the ideal division of 50/50.

Second, the role of uplink vs. downlink contention is revealed as asymmetry varies. With load asymmetry (x-axis value) of 4, Virtual Duplex approximates the ideal throughput ratio of 4 (80.46/19.54). However, WiFi-NC and 802.11 have a throughput ratio of 2.4 (70.82/29.18), 10% away from ideal

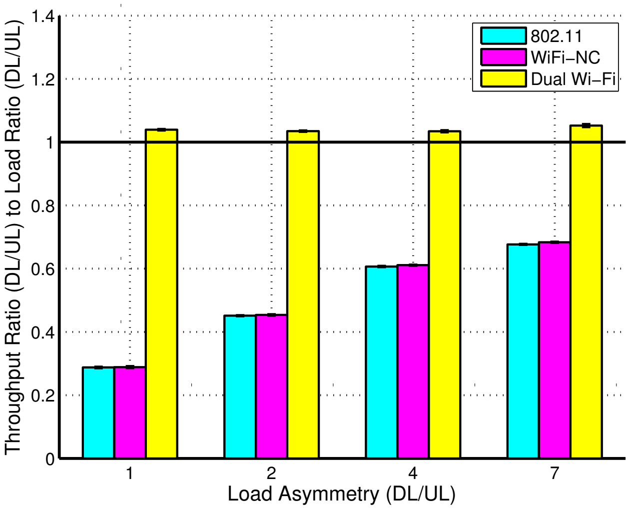


Fig. 5. Throughput ratio (DL/UL) to load ratio (DL/UL) for topologies with 1 AP and 20 clients. Note that Virtual Duplex approximates ideal ratio (value of 1) for all load asymmetries.

TABLE II. VIRTUAL DUPLEX EXPERIMENTAL AND SIMULATION THROUGHPUT RATIO (DL/UL) TO LOAD RATIO (DL/UL) FOR VARIOUS LOAD ASYMMETRIES WITH 1 AP AND 2 CLIENTS. TABLE REPORTS MEAN AND STANDARD DEVIATION.

Load Asymmetry	0.5	1	2
Hardware	1.146 (± 0.14)	1.051 (± 0.09)	0.938 (± 0.15)
Simulation	1.030 (± 0.00)	0.972 (± 0.00)	0.918 (± 0.00)

80/20 division. The slight improvement of baseline systems is because the majority of the demand is from the AP, thus uplink vs. downlink contention is lower compared to symmetric loads. However, as demonstrated in previous evaluation, client density has a significant effect in throughput to load ratio for baseline systems. In Figure 5 we show results for 20 clients, however baseline systems will further deviate from ideal as the number of clients increase.

This finding reveals that upload vs. download medium contention has a critical effect on throughput to load proportion. This conclusion drives the key reason for 802.11 and WiFi-NC to attain nearly identical performance in these cases. Both systems allow upload and download traffic to contend for the same resources and thus with each other. Baseline systems do not provide the upload and download performance isolation of Virtual Duplex, limiting these from achieving ideal throughput to load ratio.

Over-the-Air Validation: In order to validate the above simulations, we perform small-scale over-the-air experiments. We implement asymmetries of 0.5, 1 and 2, under realistic channel conditions with a two client and one AP topology. We don't compare baseline systems to Virtual Duplex because given hardware limitations, we can not provide an equal amount of total bandwidth to all three systems while adapting Virtual Duplex's bandwidth to a given traffic asymmetry (e.g. 10 MHz/5 MHz vs. 15 MHz).

Table II presents Virtual Duplex's relationship between throughput ratio and load ratio for both simulation and experimental platforms. Virtual Duplex approximates the throughput ratio to the demand ratio across all load asymmetries in both simulation and over-the-air experiments. Furthermore, we observe high proximity between all simulation and hardware results. For example, in the case of load asymmetry 1, the implementation achieved throughput to load ratios from 0.961 to 1.141 whereas simulation obtains 0.972 with negligible variance. Since all simulation results lie within one standard deviation of the hardware results, we consider our simulation results to be a comprehensive representation of over-the-air network performance.

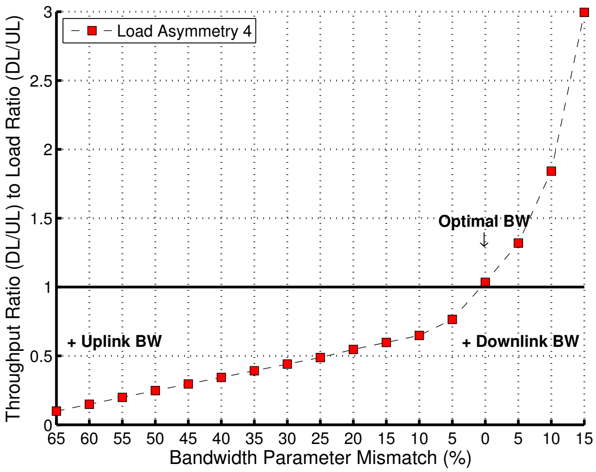


Fig. 6. Impact of mismatch in optimal bandwidth setting on throughput to load ratio (DL/UL) for asymmetric traffic.

C. Configuration of Virtual Duplex Bandwidth Division

Virtual Duplex bandwidth division can be configured to scale to traffic asymmetry and target a proportional performance ratio to a given offered load. The goal of this evaluation is to examine the change on Virtual Duplex's throughput ratio (DL/UL) to load ratio (DL/UL) as we deviate from the optimal bandwidth setting. We evaluate Virtual Duplex's robustness to the bandwidth parameter setting and we explore the case in which the bandwidth parameter setting is suboptimal compared to best setting available for the given traffic demand and network density.

Setup: We examine the *throughput (DL/UL) to load (DL/UL) ratio* obtained by all possible bandwidth parameter allocations for a given traffic load and client density. We select a network with 1 AP and 20 clients to represent a WLAN. We select traffic asymmetry of 4, to exemplify the effect of asymmetric traffic in throughput to load ratio. In Figure 6, the y-axis presents the *throughput to load ratio* obtained by each bandwidth parameter setting in the x-axis. The optimal bandwidth setting (value 0 in the x-axis) approaches the ideal throughput to load ratio (y-axis value of 1). Any value above 1 on the y-axis indicates that more throughput is given to the download traffic than demanded, whereas download traffic is underserved when the value is below 1. The x-axis depicts the mismatch from the ideal bandwidth setting as a percentage of the total bandwidth. The values to the right of the optimal bandwidth (value 0 in the x-axis) represent parameter settings with more bandwidth given to the download data channel and the values to the left of the optimal bandwidth give more bandwidth to the upload data channel.

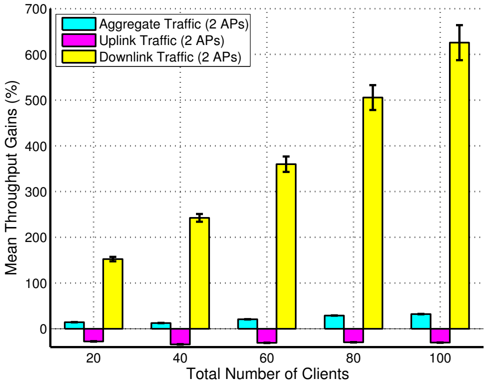
Results: In Figure 6, we explore the change in throughput to load ratio under asymmetric traffic where download traffic is 4x greater than upload traffic. Since the optimal bandwidth follows the traffic asymmetry, download can be only provided with a small percentage of extra bandwidth. We observe the optimal bandwidth (x-axis value of 0) has a throughput to load ratio of 1.03, corresponding to spectrum division 80.5/19.5, less than 1% away from the ideal 80/20 division. We observe the ideal throughput to load ratio 1.00 is crossed under a 1% mismatch towards the upload data channel, thus Virtual Duplex can obtain the ideal ratio of 1 under non-integer bandwidths, however we limit our simulation results to integer bandwidth values for realistic representation.

In the case where download is provided with 10% more bandwidth, download throughput is 8% higher than intended division 80/20 (y-value 1.8 = 87.8/12.2 DL/UL). Meanwhile when the upload data channel is provided with 10% more bandwidth, it achieves 10% more throughput (y-value 0.6 = 70.5/29.5 DL/UL) than intended. As more bandwidth is given to the upload data channel the ratio deviates from the ideal ratio of 1, this deviation accelerates past a 10% mismatch due to the severe impact of reducing download bandwidth with asymmetric load when downlink data load is greater than uplink data load. Overall, the percentage of bandwidth mismatch directly translates to the percentage divergence from ideal throughput share, however in the case of high traffic asymmetry (DL>UL) providing more bandwidth to the upload traffic has a greater impact due to spectrum underutilization.

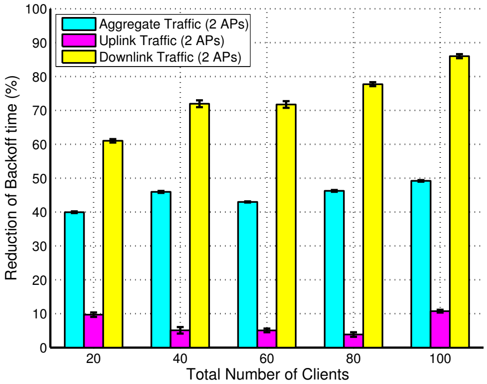
D. Gains of Virtual Duplex

Virtual Duplex's spectrum isolation and throughput to load matching translates into significant gains. Next, we explore these gains and their sources.

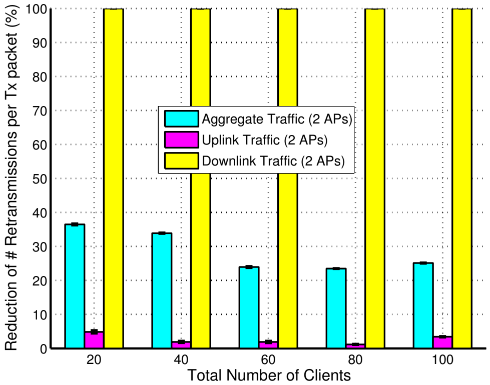
Setup: The configuration for the following experiments mirrors that of the "Impact of Contention Asymmetry" evaluation. Through simulations, we explore topologies with 2 coordinated APs to introduce downlink data contention, and vary the total number of clients between 20 to 100, equally divided across the number of APs. We measure the gains of aggregate, uplink, and downlink data traffic of Virtual Duplex as compared to 802.11. We evaluate symmetric traffic, because it presents the highest medium congestion. Results for asymmetric loads can be found at [20]. Medium access parameters follow the 802.11a standard and are the same for all nodes in all systems.



(a) Throughput gains.



(b) Reduction of backoff time.



(c) Reduction of retransmissions.

Fig. 7. Virtual Duplex gains over 802.11 for symmetric traffic with topologies of 2 APs with 20 to 100 clients.

Throughput Gains. Figure 7(a) depicts the throughput gains of Virtual Duplex over 802.11. Virtual Duplex achieves the highest gain in downlink data throughput, up to 626% for 100 clients. Such gains are obtained in scenarios with high congestion due to high client density. Since, Virtual Duplex maintains downlink data performance across any client density, we present unbounded download throughput gains that linearly increase with client density. This is because baseline downlink data performance rapidly decays as congestion increases, yielding increasing relative performance of Virtual Duplex. Virtual Duplex decreases uplink data throughput by 27 to 32%, however download throughput gains significantly outweigh throughput decay of uplink data traffic. Moreover, this decrease is targeted by Virtual Duplex's re-allocation of resources since upload traffic in 802.11 systems utilizes more spectrum than required by ideal performance to load matching. The aggregate network performance is increased approximately from 10% to 30% as client density increases, this is achieved by removal of medium contention between upload and download traffic.

Reduction of Contention Time. Backoff time before every data transmission leads to spectrum underutilization because the medium remains idle. Figure 7(b) depicts Virtual Duplex's mean reduction of backoff time per successful transmission over 802.11 as a function of client density. Since Virtual Duplex provides a download-only channel, downlink data backoff periods are low even under high client densities, providing significant reduction in backoff over 802.11 systems. Downlink data gains increase as the number of clients increase, achieving up to 86% reduction in the case of 2 APs and 100 clients. Note, Virtual Duplex can achieve higher reduction of downlink data backoff by adapting the contention window (CW) to the number of in-channel APs, however in this simulation medium contention parameters are equal in both evaluated systems. Virtual Duplex achieves an average of 8% backoff reductions on uplink data transmissions due to removal of downlink data contention even when utilizing narrower bandwidth than legacy 802.11 systems. Overall, Virtual Duplex achieves to reduce backoff time of all transmissions by 40% to 50%, meaning Virtual Duplex's medium can be utilized approximately 45% more for data transmissions.

Reduction of Retransmissions. Retransmissions affect performance by unnecessarily using spectrum resources through backoff periods and transmission of unsuccessful data, including additional inter-frame times and timeouts. Figure 7(c) depicts the mean percentage of retransmission reduction per successful transmitted packet for Virtual Duplex in comparison to 802.11. As expected, the reduction of downlink data retransmissions is the most significant, our system can eliminate (100% reduction) downlink data retransmissions even in the case of 2 in-channel coordinated APs. Uplink data retransmissions are reduced by small percentage of approximately 2-5%. The reduction of retransmissions observed by uplink data traffic are the percentage of retransmissions caused by downlink data transmissions. Overall, as a result of removing upload vs. download contention, aggregate traffic retransmissions are reduced by approximately 23-36%. Virtual Duplex on average has approximately 30% more successful transmissions, achieving a higher spectral efficiency.

IV. RELATED WORK

Virtual Duplex is the first to isolate upload and download traffic at the MAC level by providing these with independent spectrum resources and configurable bandwidth. However, there exist related work on components of Virtual Duplex such as multichannel systems, data duplexing and traffic asymmetry.

Channel allocation and Multi-channel Systems. Pre-allocating spectrum resources and achieving isolation between the traffic directions, differentiates Virtual Duplex's medium access from 802.11 medium access techniques [19], [21], where upload and download traffic share a single and common channel over time. Dual-channel system FDD provides physical directionality (i.e. physically uni-directional channels) such that data-ACK handshakes are performed in two channels, i.e a downlink data transmission occurs in the physical downlink channel while the response ACK is transmitted on the physical uplink channel [22]. In contrast to FDD, Virtual Duplex channels are bi-directional and enable independent and asynchronous non-slotted upload and download operation with arbitrary spectrum division.

Multi-channel random access systems [23], FICA [24] and WiFi-NC [9] split spectrum into multiple equal width narrow channels to increase spectral efficiency. In comparison to such approaches Virtual Duplex operates with two variable-width channels, instead of multiple equal width narrow channels. The core distinction between these approaches and Virtual Duplex is that sub-channels are pre-allocated to download or upload traffic, thus Virtual Duplex removes upload and download contention for the same resources and is able to configure spectrum resources to match traffic asymmetry. Because existing multi-channel systems [24], [9], [23] do not differentiate resources between upload and download traffic, increase in spectral efficiency is limited by upload and download contention within the narrow channels.

Full Duplex. Virtual Duplex utilizes two radio resources at the AP in order to independently and asynchronously operate both upload and download data channels. Similarly, full duplex systems implement two radio resources, but Virtual Duplex differentiates from this technique in two key aspects: spectrum resources and upload to download performance dependency. Virtual Duplex divides the allocated spectrum resources into two sub-channels, in which transmissions occur independently and asynchronously at *different* spectrum resources. However, in full-duplex systems uplink and downlink transmissions concurrently utilize the complete amount of allocated spectrum resources, thus are provided with symmetric resources [25]. Consequently, full duplex cannot treat traffic asymmetry, unless packet aggregation is utilized; however, this would reduce spectrum efficiency of full duplex due to synchronized start of transmissions and diversity in uplink and downlink load. Further, because in full duplex systems cancellation techniques are required to transmit and receive at the same time in the same spectrum resources, upload and download performance is coupled even though these don't compete for spectrum resources. Finally, full duplex is limited by the amount of self-interference cancellation it can achieve [25]. Thus application of full duplex in large-scale congested scenarios, will require complex interference cancellation schemes to achieve long distance transmissions.

Traffic and Contention Asymmetry. A common approach to address traffic asymmetry is a node-based priority, where access points are given a higher probability than clients to access the medium [24], [3], [4], [5], [11], [1], [26]. When node-based priority is implemented with *strict AP priority*, the APs begin contention before clients and the contention window range is small enough to assure clients won't contend with access points. The key issue of this approach is starvation of upload traffic. This is a key problem, because Internet traffic is bi-directional involving a request response procedure at the application layer, thus starvation of upload traffic will affect such loop. To the contrary, Virtual Duplex aids application layer bi-directionality by providing isolation of upload and download resources, which assures application traffic bi-directionality is maintained even when prioritizing download traffic.

Another approach is to prioritize the AP with overlapping client priority, where the APs on *average* gain access to the medium before the clients. Some approaches reduce the required medium idle time for the APs to begin contention [24], [1], scale the contention window size to create multiple priority levels [3], [4], [5] and modify AP's TXOP limits [11]. The key issue of this approach is that the priority given to the AP is probabilistic and dependent on the number of backlogged clients. As the number of backlogged clients increases, the clients' mean medium access probability becomes more aggressive and eventually causes the priority to shift to uplink traffic. Thus, constantly AP priority has to be adjusted to the number of backlogged clients in the network. Since priority is probabilistic it does not guarantee spectrum resources, and thus defining the throughput share between upload and download traffic is nondeterministic and scenario dependent. In contrast, Virtual Duplex provides a simple way to prioritize a traffic direction, where the given spectrum resources are guaranteed to upload or download traffic and do not depend on the number of backlogged clients in the network, allowing performance share to be deterministic.

V. CONCLUSION

In this paper, we introduce Virtual Duplex, a flexible wireless architecture that provides spectrum independence between upload and download traffic (MAC layer data-ack handshakes), that eliminates contention asymmetry and provides scalability to traffic asymmetry. Virtual Duplex utilizes the total bandwidth allocated to the system and separates it into two physical bi-directional channels: "download data channel" and "upload data channel". Each channel carries a single uni-directional MAC traffic direction, i.e. both data and its associated reverse-direction acknowledgements share a physical channel. Separating upload and download traffic at the link layer, provides flexibility to configure bandwidth resources at each channel to scale to traffic asymmetry. Furthermore, our channel design allows independent and asynchronous upload and download MAC level data-ACK transmissions, thus providing independent performance between uplink and downlink MAC level traffic. The key advantages of Virtual Duplex is the spectrum isolation between upload and download traffic that increases spectral efficiency by eliminating contention asymmetry and provides scalability and robustness to traffic asymmetry. Through evaluation on commodity hardware and simulations, we show that Virtual Duplex matches download vs. upload throughput ratio within 1% of the download vs. upload demand ratio, under any traffic asymmetry and network density. Through this matching capability, Virtual Duplex achieves unbounded download throughput gains and significant overall throughput gains, achieved by large reduction of retransmissions and contention time.

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