IEEE P802.11
Wireless LANs

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| Framework of Technical Report onFull Duplex for 802.11  |
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Abstract

This document provides new text to be considered for inclusion in the FD-TIG Technical Report on Full Duplex for IEEE 802.11.

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# ****Introduction****

**Wi-Fi products have been being widespread deployed around world with the facts of more than** three billion Wi-Fi device estimated to be shipped in 2017 and more than eight billion Wi-Fi devices currently in use [1] in order to satisfy the fast growth in user demands on data communications through, for example, home/enterprise networks, services for the public (e.g., airports, aircraft, train (stations), shopping centers and meetings, etc.), Augmented/Virtual Reality (AR/VR) and Internet of Things (IoT), and so on. **Dense deployment of Wi-Fi devices and potential high demands on data throughputs per device require the advanced Wi-Fi systems to operate with high spectrum efficiency and good performance.**

**Full Duplex (FD) is a technology to allow a device to simultaneously transmit and receive signals using the same time-frequency resource. FD can significantly increase the throughput for each allocated channel and furthermore improve the total system capacity. In addition, the inherent capability of FD can provide an opportunity to reduce round-trip latency for data transmission, which is due to transmission of ACK or feedback information and to implement an in-band relay system. Standardization of FD technology for 802.11 is considered in [2].**

This technical report on FD for IEEE 802.11 presents some key discussion results achieved in the FD TIG, which include FD use cases, FD functional requirements, technical feasibility of FD for 802.11, architecture of FD for 802.11, key FD metrics, and benefits of FD deployment.

# FD use cases

*Note: In this report, a few FD use cases such as multi-channel AP, FD mesh and multi-RAT presented in [2] and/or others should be justified as the appropriate applications of FD to satisfy the high-demanding requirements of the future 802.11.*

# FD functional requirements

## Bands and bandwidths of FD operations

### 2.4 GHz

Full Duplex capability shall be operational in these existing IEEE 802.11 2.4 GHz channels and bandwidths:

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|   | **11b DSSS** |   |  |   | **11 g/n OFDM** |   |  |   | **11n OFDM** |   |
| **Ch. Idx** | **Min (MHz)** | **Fc (MHZ)** | **Max (MHz)** | **BW (MHz)** |  | **Ch. Idx** | **Min (MHz)** | **Fc (MHZ)** | **Max (MHz)** | **BW (MHz)** |  | **Ch. Idx** | **Min (MHz)** | **Fc (MHZ)** | **Max (MHz)** | **BW (MHz)** |
|   |  | 2401 |   |   |  |   |  | 2402 |   |   |  |   |  | 2402 |   |   |
| 0 |   | 2407 |   |   |  | 0 |   | 2407 |   |   |  | 0 |   | 2407 |   |   |
| **1** | **2401** | **2412** | **2423** | **22** |  | **1** | **2402** | **2412** | **2422** | **20** |  | 1 |   | 2412 |   |   |
| 2 |   | 2417 |   |   |  | 2 |   | 2417 |   |   |  | 2 |   | 2417 |   |   |
| 3 |   | 2422 |  |   |  | 3 |   | 2422 |   |   |  | **3** | **2402** | **2422** | **2442** | **40** |
| 4 |   | 2427 |   |   |  | 4 |   | 2427 |   |   |  | 4 |   | 2427 |   |   |
| 5 |   | 2432 |   |   |  | **5** | **2422** | **2432** | **2442** | **20** |  | 5 |   | 2432 |   |   |
| **6** | **2426** | **2437** | **2448** | **22** |  | 6 |   | 2437 |   |   |  | 6 |   | 2437 |   |   |
| 7 |   | 2442 |   |   |  | 7 |   | 2442 |   |   |  | 7 |   | 2442 |   |   |
| 8 |   | 2447 |  |   |  | 8 |   | 2447 |   |   |  | 8 |   | 2447 |   |   |
| 9 |   | 2452 |   |   |  | **9** | **2442** | **2452** | **2462** | **20** |  | 9 |   | 2452 |   |   |
| 10 |   | 2457 |   |   |  | 10 |   | 2457 |   |   |  | 10 |   | 2457 |   |   |
| **11** | **2451** | **2462** | **2473** | **22** |  | 11 |   | 2462 |   |   |  | **11** | **2442** | **2462** | **2482** | **40** |
| 12 |   | 2467 |   |   |  | 12 |   | 2467 |   |   |  | 12 |   | 2467 |   |   |
| 13 |   | 2472 |  |   |  | **13** | **2462** | **2472** | **2482** | **20** |  | 13 |   | 2472 |   |   |
|   |   |   |   |   |  |   |   | 2482 |   |   |  |   |   | 2482 |   |   |

3.1.2 5 GHz

Full Duplex capability shall be operational in these existing IEEE 802.11 5 GHz channels and bandwidths:

| **Ch. Idx** | **Min (MHz)** | **Fc (MHZ)** | **Max (MHz)** | **BW (MHz)** |  | **Ch. Idx** | **Min (MHz)** | **Fc (MHZ)** | **Max (MHz)** | **BW (MHz)** |  | **Ch. Idx** | **Min (MHz)** | **Fc (MHZ)** | **Max (MHz)** | **BW (MHz)** |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|   |  | 5170 |   |   |  |   |   | 5170 |   |   |  |   |  | 5170 |   |   |
| **36** | **5170** | **5180** | **5190** | **20** |  | 36 |   | 5180 |   |   |  | 36 |   | 5180 |   |   |
| 38 |   | 5190 |   |   |  | **38** | **5170** | **5190** | **5210** | **40** |  | 38 |   | 5190 |   |   |
| **40** | **5190** | **5200** | **5210** | **20** |  | 40 |   | 5200 |   |   |  | 40 |   | 5200 |   |   |
| 42 |   | 5210 |   |   |  | 42 |   | 5210 |   |   |  | **42** | **5170** | **5210** | **5250** | **80** |
| **44** | **5210** | **5220** | **5230** | **20** |  | 44 |   | 5220 |  |  |  | 44 |   | 5220 |   |   |
| 46 |   | 5230 |   |   |  | **46** | **5210** | **5230** | **5250** | **40** |  | 46 |   | 5230 |   |   |
| **48** | **5230** | **5240** | **5250** | **20** |  | 48 |   | 5240 |   |   |  | 48 |   | 5240 |   |   |
| 50 |   | 5250 |   |   |  | 50 |   | 5250 |   |   |  | 50 |   | 5250 |   |   |
| **52** | **5250** | **5260** | **5270** | **20** |  | 52 |   | 5260 |   |   |  | 52 |   | 5260 |   |   |
| 54 |   | 5270 |   |   |  | **54** | **5250** | **5270** | **5290** | **40** |  | 54 |   | 5270 |   |   |
| **56** | **5270** | **5280** | **5290** | **20** |  | 56 |   | 5280 |   |   |  | 56 |   | 5280 |   |   |
| 58 |   | 5290 |   |   |  | 58 |   | 5290 |   |   |  | **58** | **5250** | **5290** | **5330** | **80** |
| **60** | **5290** | **5300** | **5310** | **20** |  | 60 |   | 5300 |   |   |  | 60 |   | 5300 |   |   |
| 62 |   | 5310 |   |   |  | **62** | **5290** | **5310** | **5330** | **40** |  | 62 |   | 5310 |   |   |
| **64** | **5310** | **5320** | **5330** | **20** |  | 64 |   | 5320 |   |   |  | 64 |   | 5320 |   |   |
| 66 |   | 5330 |  |   |  |   |   | 5330 |  |   |  | 66 |   | 5330 |  |   |
| 98 |  | 5490 |   |   |  | 98 |  | 5490 |   |   |  | 98 |  | 5490 |   |   |
| 100 | **5490** | **5500** | **5510** | **20** |  | 100 |   | 5500 |   |   |  | 100 |   | 5500 |   |   |
| 102 |   | 5510 |   |   |  | **102** | **5490** | 5510 | **5530** | **40** |  | 102 |   | 5510 |   |   |
| **104** | **5510** | **5520** | **5530** | **20** |  | 104 |   | 5520 |   |   |  | 104 |   | 5520 |   |   |
| 106 |   | 5530 |   |   |  | 106 |   | 5530 |   |   |  | **106** | **5490** | **5530** | **5570** | **80** |
| **108** | **5530** | **5540** | **5550** | **20** |  | 108 |   | 5540 |   |   |  | 108 |   | 5540 |   |   |
| 110 |   | 5550 |   |   |  | **110** | **5530** | **5550** | **5570** | **40** |  | 110 |   | 5550 |   |   |
| **112** | **5550** | **5560** | **5570** | **20** |  | 112 |   | 5560 |   |   |  | 112 |   | 5560 |   |   |
| 114 |   | 5570 |   |   |  | 114 |   | 5570 |   |   |  | 114 |   | 5570 |   |   |
| **116** | **5570** | **5580** | **5590** | **20** |  | 116 |   | 5580 |   |   |  | 116 |   | 5580 |   |   |
| 118 |   | 5590 |   |   |  | **118** | **5570** | **5590** | **5610** | **40** |  | 118 |   | 5590 |   |   |
| **120** | **5590** | **5600** | **5610** | **20** |  | 120 |   | 5600 |   |   |  | 120 |   | 5600 |   |   |
| 122 |   | 5610 |   |   |  | 122 |   | 5610 |   |   |  | **122** | **5570** | **5610** | **5650** | **80** |
| **124** | **5610** | **5620** | **5630** | **20** |  | 124 |   | 5620 |   |   |  | 124 |   | 5620 |   |   |
| 126 |   | 5630 |   |   |  | **126** | **5610** | **5630** | **5650** | **40** |  | 126 |   | 5630 |   |   |
| **128** | **5630** | **5640** | **5650** | **20** |  | 128 |   | 5640 |   |   |  | 128 |   | 5640 |   |   |
| 130 |   | 5650 |   |   |  | 130 |   | 5650 |   |   |  | 130 |   | 5650 |   |   |
| **132** | **5650** | **5660** | **5670** | **20** |  | 132 |   | 5660 |   |   |  | 132 |   | 5660 |   |   |
| 134 |   | 5670 |   |   |  | **134** | **5650** | **5670** | **5690** | **40** |  | 134 |   | 5670 |   |   |
| **136** | **5670** | **5680** | **5690** | **20** |  | 136 |   | 5680 |   |   |  | 136 |   | 5680 |   |   |
| 138 |   | 5690 |   |   |  | 138 |   | 5690 |   |   |  | **138** | **5650** | **5690** | **5730** | **80** |
| **140** | **5690** | **5700** | **5710** | **20** |  | 140 |   | 5700 |   |   |  | 140 |   | 5700 |   |   |
| 142 |   | 5710 |   |   |  | **142** | **5690** | **5710** | **5730** | **40** |  | 142 |   | 5710 |   |   |
| **144** | **5710** | **5720** | **5730** | **20** |  | 144 |   | 5720 |   |   |  | 144 |   | 5720 |   |   |
|   |   | 5730 |  |   |  |   |   | 5730 |  |   |  | 146 |   | 5730 |  |   |
| 147 |  | 5735 |   |   |  | 147 |  | 5735 |   |   |  | 147 |  | 5735 |   |   |
| **149** | **5735** | **5745** | **5755** | **20** |  | 149 |   | 5745 |   |   |  | 149 |   | 5745 |   |   |
| 151 |   | 5755 |   |   |  | **151** | **5735** | **5755** | **5775** | **40** |  | 151 |   | 5755 |   |   |
| **153** | **5755** | **5765** | **5775** | **20** |  | 153 |   | 5765 |   |   |  | 153 |   | 5765 |   |   |
| 155 |   | 5775 |   |   |  | 155 |   | 5775 |   |   |  | **155** | **5735** | **5775** | **5815** | **80** |
| **157** | **5775** | **5785** | **5795** | **20** |  | 157 |   | 5785 |   |   |  | 157 |   | 5785 |   |   |
| 159 |   | 5795 |   |   |  | **159** | **5775** | **5795** | **5815** | **40** |  | 159 |   | 5795 |   |   |
| **161** | **5795** | **5805** | **5815** | **20** |  | 161 |   | 5805 |   |   |  | 161 |   | 5805 |   |   |
| 163 |   | 5815 |   |   |  | 163 |   | 5815 |  |   |  | 163 |   | 5815 |  |   |
| **165** | **5815** | **5825** | **5835** | **20** |  | 165 |  | 5825 |  |   |  | 165 |  | 5825 |  |   |
|   |   | 5835 |   |   |  |   |   |   |   |   |  |   |   |   |   |   |

| **Ch. Idx** | **Min (MHz)** | **Fc (MHZ)** | **Max (MHz)** | **BW (MHz)** |
| --- | --- | --- | --- | --- |
|   |  | 5170 |   |   |
| 36 |   | 5180 |   |   |
| 38 |   | 5190 |   |   |
| 40 |   | 5200 |   |   |
| 42 |   | 5210 |   |   |
| 44 |   | 5220 |   |   |
| 46 |   | 5230 |   |   |
| 48 |   | 5240 |   |   |
| **50** | **5170** | **5250** | **5330** | **160** |
| 52 |   | 5260 |   |   |
| 54 |   | 5270 |   |   |
| 56 |   | 5280 |   |   |
| 58 |   | 5290 |   |   |
| 60 |   | 5300 |   |   |
| 62 |   | 5310 |   |   |
| 64 |   | 5320 |   |   |
| 66 |   | 5330 |  |   |
| 98 |  | 5490 |   |   |
| 100 |   | 5500 |   |   |
| 102 |   | 5510 |   |   |
| 104 |   | 5520 |   |   |
| 106 |   | 5530 |   |   |
| 108 |   | 5540 |   |   |
| 110 |   | 5550 |   |   |
| 112 |   | 5560 |   |   |
| **114** | **5490** | **5570** | **5650** | **160** |
| 116 |   | 5580 |   |   |
| 118 |   | 5590 |   |   |
| 120 |   | 5600 |   |   |
| 122 |   | 5610 |   |   |
| 124 |   | 5620 |   |   |
| 126 |   | 5630 |   |   |
| 128 |   | 5640 |   |   |
| 130 |   | 5650 |   |   |
| 132 |   | 5660 |   |   |
| 134 |   | 5670 |   |   |
| 136 |   | 5680 |   |   |
| 138 |   | 5690 |   |   |
| 140 |   | 5700 |   |   |
| 142 |   | 5710 |   |   |
| 144 |   | 5720 |   |   |
| 146 | 5650 | 5730 | 5810 | 160 |
| 147 |   | 5735 |   |   |
| 149 |   | 5745 |   |   |
| 151 |   | 5755 |   |   |
| 153 |   | 5765 |   |   |
| 155 |   | 5775 |   |   |
| 157 |   | 5785 |   |   |
| 159 |   | 5795 |   |   |
| 161 |   | 5805 |   |   |
| 163 |   | 5815 |  |   |
| 165 |  | 5825 |  |   |
|   |   |   |   |   |



## Throughput over an allocated bandwidth

SIC technology in conjunction with a FD MAC protocol allows simultaneous transmit and receive over the same frequency spectrum. Compared to existing HD, Wi-Fi systems, FD Wi-Fi systems can at a minimum double the data throughput per channel in BSSs without hidden nodes and by a factor of 10x or more for BSSs with hidden nodes*.*

### FD Throughput gain without hidden nodes [5]

Table 1 summarizes the results of an extensive series of S-CW FD simulations performed by D. Marlali [5] in which he varied the self-interference cancellation levels from complete cancellation (‘λ = ∞) to a level with only 40% SIC (‘λ = 0.4) in a BSS without any hidden nodes and the number of STAs varied from 40 to 2. Similar FD Gains were reported in [12] for a different FD protocol.

Table 1: FD Gains observed during simulations without hidden nodes

|  |  |  |  |
| --- | --- | --- | --- |
| **SIC Levels** | **Number of Hidden Nodes** | **FD Gain w/ Exponential pkt size Distribution w/ mean=400 octets** | **FD Gain w/ constant pkt size = 1500 octets** |
| ‘λ = ∞ | 0 | 1.27 – 1.59 | 1.56 – 2.10 |
| ‘λ = 0.6 | 0 | 1.27 – 1.47 | 1.46 – 1.90 |
| ‘λ = 0.4 | 0 | 1.06 – 1.04 | 1.20 – 1.30 |
|  |  | *Decreasing number of STAs (40 to 2)* |

### FD Throughput gain with hidden nodes [5]

Although Table 1 above confirms what critics of single frequency full duplex have been saying for some time, Table 2 provides a more compelling argument for the significant positive impact that a single frequency full duplex protocol operating in a densely populated BSS with hidden nodes can have on Full-duplex Gain. The column labeled FD Gain w/ constant pkt-size=1500 octets indicates that when the number of hidden nodes is equal to 10 and the number of STAs is equal to 40 in a BSS the FD Gain can be greater than 10x for SIC levels varying between 40% to 100%.

Table 2: FD Gains observed during simulations with hidden nodes

|  |  |  |  |
| --- | --- | --- | --- |
| **SIC Levels** | **Number of Hidden Nodes** | **FD Gain w/ Exponential pkt size Distribution w/ mean=400 octets** | **FD Gain w/ constant pkt size = 1500 octets** |
| ‘λ = ∞ | 1 | 1.06 – 1.40 | 1.56 – 2.29 |
|  | 5 | 1.38 – 2.48 | 1.50 – 7.11 |
|  | 10 | 1.27 – 3.63 | 1.68 – **14.36** |
| ‘λ = 0.6 | 1 | 0.99 – 1.37 | 1.49 – 2.17 |
|  | 5 | 1.17 – 2.40 | 1.44 – 6.93 |
|  | 10 | 1.23 – 3.37 | 1.64 – **13.47** |
| ‘λ = 0.4 | 1 | 0.78 – 1.15 | 1.15 – 1.87 |
|  | 5 | 0.95 – 1.90 | 1.21 – 5.63 |
|  | 10 | 1.04 – 2.74 | 1.36 – **10.66** |
|  |  | *Increasing number of STAs (2 to 40)* |

## Latency enhancement

The FD enhancement improves the latency of 802.11 systems by:

* Improving the random access mechanism for channel access: FD capability in to AP and STA allows for implementation of scheduled-like channel access functions in the network. The frame structures can allow for transmission of control channel from STA to AP while AP is sending data to STA, and vice-versa.
* Collision detection: The listen-while-transmit capability of the FD capable AP and/or STA improves the success of channel access in dense environment.
* Exploiting hidden terminal problem: FD capability at AP can be used to schedule transmissions to/from two hidden terminal. The AP can collect data from STA and form an interference map. The AP can then use this interference map to schedule transmission and reception from the STA to improve the spectrum access efficiency.
* Eliminating need of RTS/CTS frames: Listen-while transmit capability allows for eliminating RTS/CTS frames to avoid collisions. The AP and/or STA can sense the channel during their transmission and can pre-emptively stop transmissions when they sense transmissions from other nodes.

{Editor Note: Awaiting S-CW FD simulation results that will provide comparative latency data for a FD use case versus a HD use case.}

## FD capability of AP and STA

Full Duplex (FD) capable APs and STAs are required to operate in either of these Basic Service Sets (BSS)s:

* A homogeneous BSS in which the AP and all of its associated STAs are FD capable, or
* A heterogeneous BSS in which the AP is FD capable and its associated STAs are either:
	+ All Half Duplex (HD) capable, or
	+ A mixture of FD and HD capable STAs

## Backward compatibility and co-existence with legacy 802.11 devices

Any IEEE 802.11 device (e.g. STA or AP) that supports full duplex functionality should be able to operate in a heterogeneous 802.11 network populated with a variety of 802.11 devices defined in the IEEE Std 802.11 2016 (e.g. .11n(HT), .11ac(VHT), …) and the IEEE P802.11ax/D3.0 (i.e. HEW WLAN).

## ~~Hidden node mitigation [5] (~~see 3.2.2~~)~~

~~{Editor Note: Need text describing the overall improvement in performance of a BSS populated with devices that are hidden from each other.}~~

# FD Technical Feasibility

## Technical survey

### Current instantiations of Full Duplex PHY functionality

Table 1 lists six approaches and their attributes for enabling full duplex PHY behaviour in a wireless networking system.

Table 3: Comparison of Full Duplex PHY Approaches

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | **Approach 1** | **Approach 2** | **Approach 3** | **Approach 4** | **Approach 5** | **Approach 6** |
|  | Antenna Separation [6] | Meta-materials based circulator | Antenna Polarization [8] | Delay and Subtract [9] | Photonics [10] | Hybrid RF/ Photonic/ Digital Baseband |
| Bandwidth | 5MHz | 1MHz | 20MHz | 20/40MHz | 10MHz | 800MHz |
| Drift Tolerance | Low | High | Low | Moderate | Moderate | High |
| Scatter Tolerance | No | No | No | No | No | Yes |
| Environ-ment Fluctuation  | Intolerant | Intolerant | Intolerant | Intolerant | Intolerant | Tolerant |
| MIMO capability | Limited | Limited | Yes | Yes | Limited | Yes |
| Form Factor | Antenna spacing | Small | Small | Small | Small | Chip-scale |

### Current Full Duplex MACs

A review of the current technical literature regarding MAC protocols that support the Full Duplex (FD) exchange of packets in an IEEE 802.11 network revealed an extensive bibliography of papers. Out of this extensive list, these, at the moment, three FD capable MAC protocols were selected as indications of the evolving maturity of the full duplex protocols. The criteria used to select these three protocols are listed in the first column labelled Attributes.

Table 4: FD MAC Comparisons

| **Attributes** | **S-CW Full Duplex [5]** | **SRB-MAC [6]** | **STR-MAC [11]** |
| --- | --- | --- | --- |
| Organization | Sabanaci U. | Rice U. | Toshiba Research |
| Modifications of existing Frame Formats | 2 bits in existing MAC Hdr ctrl field; 10 bit *next\_bo* field at head of payload | Adds a 13 bit FD Hdr between the MAC Hdr and the Payload | FD Capability Info Field; 1-bit mod of reserved bits in CTS (CTS\_FD) |
| New MAC Mechanisms | Synchronized contention window | Shared random backoff; virtual backoff; header snooping | Adaptive Tx & ACK TO |
| Supports Heterogeneous FD/HD WLANS | Yes | If HD Nodes support snooping, then Yes, else No | Yes |
| Supports Homogeneous FD WLAN | Yes | Yes | Yes |
| BiDirectional FD | Yes | Yes | Yes |
| UniDirectional FD | Yes | Yes | Yes |
| Hidden Node Mitigation | Yes via FD & FDmaster bits in MAC Hdr ctrl fld. | Via Snooping | Via RTS/CTS |
| Backwards Compatible w/ HD WiFi | Yes | If HD Nodes support snooping, then Yes, else No | Yes |
| FD,Throughput Gain in a BSS w/o hidden nodes | 1.6x to 2.1x(40 to 2 nodes) | ??? | ??? |
| FD, Throughput Gain in a BSS w/ hidden nodes  | 1.7x to 14.4x(2 to 40 nodes) | ??? | ??? |
|  |  |  |  |

### Real World Implementation of Full Duplex Operation in DOCSIS 3.1-FDX

DOCSIS 3.1 R-PHY [12] and DOCSIS 3.1-FDX [13] provide yet another example of a wired protocol that borrows heavily from the wireless communications domain (e.g.11n-OFDM and 11ax OFDMA). Both DOCSIS 3.1 documents define the use of a full duplex protocol between cable modems (CM) and cable modem termination systems (CMTS) in a hybrid fiber/coax (HFC) network as illustrated in Figure 1.



Figure 1: Example Cable Network based upon DOCSIS 3.1-FDX

The goals of this specification are to:

* Increase the capacity (i.e. total available bandwidth) of the current HFC network infrastructure without replacing existing coax to-the-home/buisness with fiber-to-the-home/business
* Provide backwards compatibility for CMTSs and CMSs based upon earlier versions of DOCSIS specifications (e.g. CMTSs: 3.0, 2.0, and 1.1; CMSs:3.1, 3.0). For instance, continued support for the 16-QAM, 64-QAM, 128-QAM and 256-QAM downstream modulation schemes and the QPSK, 8-QAM, 16-QAM, 32-QAM and 64-QAM upstream modulation schemes in DOCSIS 3.0 are mandatory and required.
* Improve the scalability of hybrid-fiber-coax (HFC) network infrastructure via
	+ higher modulation schemes in both the downstream and upstream data flows as defined in DOCSIS 3.1 R-PHY: For example, the addition of 512-QAM, 1024-QAM, 2048-QAM, and 4096-QAM are new, mandatory modulation schemes that are unique to DOCSIS 3.1 R-PHY and are not present in earlier versions of DOCSIS. In addition, DOCSIS 3.1 R-PHY defines these two new optional modulations 8192-QAM and 16384-QAM
	+ new spectrum usage options that increase the amount of available bandwidth, while at the same time maintaining backwards compatibility with earlier versions of DOCSIS.
	+ Improved energy efficiency.
* Increase bi-directional peak speeds by enabling symmetrical multi-gigabit per second data rates between the CMTS and CMs in both the downstream and upstream data flows (see Table 3). Key enabling technologies in support of this goal are ***robust echo cancellation, co-channel interference, adjacent channel interference and self-interference mitigation techniques***.

Table 5: The Evolution of DOCSIS Downstream and Upstream Data rates

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | **DOCSIS 1.0** | **DOCSIS 1.1** | **DOCSIS 2.0** | **DOCSIS 3.0** | **DOCSIS 3.1** | **Full Duplex DOCSIS 3.1** |
| Highlights | Initial cable broadband technology | Added VoIP | Increased upstream data rate | Increased capacity & data rates | Continued increases in capacity and data rates | Symmetrical data flows w/ increased upstream data rates  |
| Downstream Capacity | 40 Mbps | 40 Mbps | 40 Mbps | 1 Gbps | 10 Gbps | 10 Gbps |
| UpStream Capacity | 10 Mbps | 10 Mbps | 30 Mbps | 100 Mbps | 1-2 Gbps | 10 Gbps |
| Production Date | 1997 | 2001 | 2002 | 2006 | 2013 | 2017 |

A major Multi-system Operator (MSO) is currently field testing a hybrid RF/Photonic analog frontend based upon the requirements described in the DOCSIS 3.1-R-PHY and DOCSIS 3.1-FDX specifications. Key test items of this field test system, as illustrated in Figure 1, are support for:

* Independently configurable downstream OFDM channels in which each channel may occupy a spectrum of up to 192 MHz with either 7680, 25 kHz subcarriers or 3840, 50 kHz subcarriers encompassing the frequency range between 108MHz and 684MHz (e.g. three 192 MHz OFDM channels);
* Independently configurable upstream OFDMA channels in which each channel may occupy a spectrum of up to 95 MHz with either 3800, 25 kHz subcarriers or 1920, 50 kHz subcarriers encompassing the frequency range between 108 MHz and 684 MHz (e.g. six 95 MHz OFDMA channels).
* Full duplex functionality between the CMs and CMTS, which is dependent upon the implementation of effective echo cancellation techniques to mitigate
	+ Adjacent Leakage-interference (ALI)
	+ Adjacent Channel Interference (ACI)
	+ Co-Channel Interference (CCI)
* Backwards compatibility with CMs and CMTSs based upon earlier versions of DOCSIS.

Preliminary results from this field test are indicating that the Hybrid RF/Photonics analog frontend is meeting/exceeding the DOCSIS 3.1-R-PHY requirements for

* Echo cancellation at each CM of at least 35 dBm, which is effectively mitigating the effects of
	+ Adjacent Leakage-interference (ALI)
	+ Adjacent Channel Interference (ACI)
	+ Co-Channel Interference (CCI)

## FD operations within a BSS

### Self-interference sources and cancellation level requirements

Figure 2 illustrates the locations of various parasitic self-interference mechanisms present in a full duplex transceiver that need to be mitigated:



|  |
| --- |
| BB TxBB RxPALNA**Antenna Interface**DACADCFull Duplex TransceiverParasitic Self-Interferers |

Figure 2: Self Interference Mechanisms in a Full Duplex Transceiver

Whereas Figure 3 illustrates the relative magnitudes of the transmitted and received signal levels in a bi-directional full duplex use case along with the relative magnitudes of the interference signal levels after each stage of filtering.

**Receiver Path Loss**

Using friis equation,

Where the terms in the equation are:

* Pr —Received power in watts.
* Pt — Peak transmit power in watts.
* Gt — Transmitter gain.
* Gr — Receiver gain.
* λ — operating frequency wavelength in meters.
* L — General loss factor to account for both system and propagation loss.
* R — Range from the transmitter to the receiver.

Receive power at the receive antenna can be calculated.

**Self Interference Path Loss**

Where the terms in the equation are:

* Pr — Reflected received power in watts.
* Pt — Peak transmit power in watts.
* Gt — Transmitter gain.
* Gr — Receiver gain.
* λ — operating frequency wavelength in meters.
* σ — Reflector's non-fluctuating cross section in square meters.
* L — General loss factor to account for both system and propagation loss.
* Rt — Range from the transmitter to the reflector.
* Rr — Range from the receiver to the reflector.

Using the above equation, we can calculate the values of Psi1 and Psi2.

|  |
| --- |
|  Tx1Rx1Tx2Rx2 |
| **Prsi2****Psi2****PRx2****PTx2** **Prsi1****PTx1****Psi1****PRx1**~35-55 dB~40-50 dB |
| **PTxi =** | Transmit signal power level from each transceiver “i” = 20dBm |
| **PRxi =** | Received signal power level at each transceiver “i” = -45dBm at 10m |
| **Psii =** | Self-interference(SI) power level within each transceiver “i” |
| **Prsii =**  | Residual SI level within each transceiver “i” after analog and digital BB cancellations = xx dBm |

Figure 3: Relative Signal Strengths as measured in two Full-duplex transceivers with SIC Filtering.

### Potential techniques for self-interference cancellation

{EditorNote: Yan Xin has text and a diagram for this section that he will use here}

### Scheduling in FD for 802.11

## FD operations over overlapping BSS (OBSS)

## Impacts on the 802.11 standard

{EditorNote: This clause may contain text that will be redundant with items listed in Table 4. The goal should be one in which the impact upon legacy 802.11 MAC implementations is minimal}

# FD Architectures in 802.11 WLANs

## Asymmetric (e.g. Unidirectional) FD for 802.11

In Asymmetric/Unidirectional data flows in which the source STA\_1 and the destination STA\_2 are unable to hear each other, a FD capable AP is able to simultaneously receive from STA\_1 and transmit to STA\_2. {EditorNote: Add Kome O.’s diagram here illustrating the principle}

## Symmetric (e.g. Bidirectional) FD for 802.11

In a symmetrical/Bidirectional data flow, a FD capable AP and one of its associated FD capable STAs are able to simultaneously exchange two unique data flows (e.g STA\_1 to AP; AP to STA\_1) {EditorNOte: Add Kome O.’s diagram here illustrating the principle.}

# FD Benefits and Challenges

# Economic Feasibility

Over the past two-plus decades, each IEEE Wi-Fi group that proposed an addition to the IEEE 802 LMSC standard provided evidence for the economic feasibility of their proposal. Evidence such as: balanced costs, known cost factors, installation costs, operational costs and estimated market size. In keeping with that tradition, the FD-TIG provides its perspective for each of these items:

1. Balanced costs (infrastructure versus attached stations)

While there will be an initial small cost increment for each Full Duplex enabled access point, infrastructure utilization will be increased significantly by the addition of Full Duplex, which will enable each access point to handle more client STAs and thereby either reduce or remove the need to add and install more access points. This savings far outweighs the added cost to purchase and install new access points. For user devices, there will similarly be a small cost increment that will be no different than that encountered during a typical upgrade cycle with performance enhancements such as from 802.11n to 802.11ac or 802.11ac to 802.11ax. Depending upon the implementation, there can also be some component savings (e.g. removal of some filters/diplexers), thus offsetting the total cost when adding full duplex capability.

1. Known cost factors

Support of the proposed standard will likely require manufacturers to develop a modified radio, modem and firmware. This is similar in principle to the transition between IEEE 802.11n and IEEE 802.11ac as well as in previous iterations of IEEE 802.11 enhancements. By utilizing existing high-volume IC wafer, packaging, and testing facilities, devices that implement Full Duplex capable PHYs are expected to be of similar cost to current front end/ filter solutions.

1. Consideration of installation costs

Since Full Duplex AP\_s and STA\_s are required to be backwards compatible with earlier versions of installed dot\_11 devices, the installation of Full Duplex enabled AP\_s and STA\_s will follow a ramp function instead of a step function thereby minimizing the cost of installation.

1. Consideration of operational costs (e.g. energy consumption)

Devices that implement Full Duplex are expected to require similar physical and electrical connections to existing front end and standard RFIC devices. Power consumption and thermal requirements are also expected to be similar to standard RFIC / filter solutions.

1. Market size [14]:

The market size for Full Duplex enabled Wi-Fi chipsets is expected to be 500M units in 2021 and 800M units in 2022, which equates to 20% of the combined 802.11ac and 802.11ax market in 2021 and 30% of the combined market in 2022. These market projections are derived from a WFA sponsored ABI forecast for the volume of Wi-Fi chipsets to be delivered as illustrated in Figure 4. In addition, it is assumed that pre-standard Infrastructure solutions could be available before completion of the standard to help drive market learning, uptake and cost reduction.



Figure 4: Projected Wi-Fi chipset shipments

# Recommendations

# References

[1] Wi-Fi Alliance press, January 2017.

[2] IEEE 802.11: 11-18-0191-01-0wng-full-duplex-for-802-11.

[3] IEEE 802.11: 11-18-0448-00-00fd-full-duplex-benefits-and-challenges.

[4] IEEE Standard for Information Technology-telecommunications and Information Exchange Between Systems Local and Metropolitan Area Networks-specific Requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, IEEE Std 802.11-2016.

[5] D. Marlali and O. Gurbuz, “Design and performance analysis of a full-duplex MAC protocol for wireless local area networks” Ad Hoc Networks 67, pp. 53-67, Oct 2017.

[6] X. Xie, X. Zhang, “Does Full-Duplex Double the Capacity of Wireless Networks?”, IEEE INFOCOM 2014, pp. 253-261, 2014

[7]A. Sahai, G. Patel and A. Sabharwal, “Pushing the limits of Full-duplex: Design and Real-time Implementation”, Technical Report TREE 1104, Rice University, pp. 1-6, July 2011.

[8] N. Reiskarimian, T. Dinc, J. Zhou, T. Chen, M. Baraani Dastjerdi, J. Diakonikolas, G. Zussman, and H. Krishnaswamy, "A One-Way Ramp to a Two-Way Highway: Integrated Magnetic-Free Non-Reciprocal Antenna Interfaces for Full Duplex Wireless," invited and submitted to IEEE Microwave Magazine

[9] T. Dinc, and H. Krishnaswamy, “Architectures, Antennas and Circuits for Millimeter-wave Wireless Full-Duplex Applications”, Thesis, Columbia University, 2018,

[10] D. Bharadia, E. McMilin and S. Katti, “Full Duplex Radios”, SIGCOMM’13, pp. 375-386, Aug. 2013

[11] [M. P. Chang, M. P. Fok, A. Hofmaier, and P. R. Prucnal, “Optical analog self-interference cancellation with electro-absorption modulators,” IEEE Microwave. Wireless Component Letters., vol. 23, no. 2, pp. 99–101, Feb. 2013.](http://ee.princeton.edu/research/prucnal/sites/default/files/06423220.pdf)

[12] A. Aijaz and P. Kulkarni, “Simultaneous Transmit and Receive Operation in Next Generation IEEE 802.11 WLANs: A MAC Protocol Design Approach”, IEEE Wireless Communications, pp. 128-135, Dec 2017

[13] Data-Over-Cable Service Interface Specifications DOCSIS 3.1: Physical Layer Specification, Cable Television Laboratories, Inc., Dec 2017

[14] Data-Over-Cable Service Interface Specifications DOCSIS 3.1: MAC and Upper Layer Protocols Interface Specification, Cable Television Laboratories, Inc., May 2018

[15] Wi-Fi Shipments by Frequency Band, Wi-Fi Alliance/ABI Research, Feb. 2018