In-band Full Duplex Wireless Communications and Networking for IoT Devices: Progress, Challenges and Opportunities

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***Abstract*—The new era of IoT devices call for wireless communications with high spectral efficiency because of the congested spectral space in reality. Current wireless communication systems work at half duplex mode in an either time-division(TDD) or frequency-division(FDD) approach to transmit and receive wireless signals. Half duplex results in poor spectral efficiency because only unidirectional communications are allowed. Recent research has aimed at enabling in-band full duplex (IBFD) wireless communication that allows a wireless node for simultaneous transmission and reception of signals. IBFD has potentials to double spectra efficiency. This paper investigates the research background and progress of IBFD. It formulates the research problems and opportunities. It also summarizes the performance of literature solutions and compares their strengths and weakness.**

I. Introduction

Future wireless communications and networking for IoT devices summon for highly efficient algorithms, architectures and protocols in spectral utilization. A number of organizations in different countries and regions have launched programs for 5G such as 5GNOW [1]–[4] and Mobile and wireless communications Enablers for the Twenty-twenty Information Society (METIS) [5]. Key technologies for future wireless communication systems aim to approach to wireless channel capacity via increased spectral efficiency, spectrum extension and network densification using many small cells [6]. Furthermore, the Third Generation Partnership Project (3GPP) has proposed a draft version as a roadmap for the 5G system [7]. This proposal includes requirements such as higher spectral and energy efficiency, lower end-to-end latency, and the ability to support massive numbers of nodes for future wireless communication systems [7].

Wireless radios today generally work on half duplex. Namely, on a single channel, they can either transmit or receive, but not both simultaneously. Half-duplex radio yields many limitations to the protocols and architectures of wireless communications and networking today, such as media access control(MAC) bit rate adaptation and self interference. As a promising technology for next-generation wireless communications and networks, in-band full-duplex wireless not only has the potential to double the spectrum efficiency in physical layer, but also can help solve some important problems in existing wireless networks, such as hidden terminals, loss of throughput due to congestion, and large end-to-end delays [8]. Additionally, full-duplex relay can significantly improve throughput and coverage [9]–[11].

Traditional wireless devices have to operate in half-duplex mode to avoid the high-powered self-interference that is generated when transmission and reception coexist in time and frequency. It was even believed that the simultaneous transmission and reception of signals on the same frequency is not possible [12]. The tremendous potential benefits of full duplex wireless have however recently attracted many researchers to explore solutions to build such wireless interfaces as that it can reduce or mitigate self-interference. Namely, if a wireless node can cancel its own signal, then its own transmissions will not damage its received packets. As a result, it can simultaneously transmit and receive.

In the rest of this paper, Section II provides a brief research background and literacy of in-band full duplex wireless. Comparison and contrast between half duplex and full duplex wireless are then presented in Section III. Critical research problems and opportunities of full duplex wireless are next discussed in Section IV. Then, Section V summarizes the literature solutions proposed to cancel self-interference, which is followed by a summary of latest MAC protocols proposed for IBFD in Section VI. The performance of literature IBFD solutions is reviewed in Section VII. This paper is finally concluded in Section VIII.

II. Background

Full-duplex wireless experimental demonstrations for narrow-band wireless communication systems were first reported in 1998 [13]. Since then, a few of researchers have proposed various methods and implementations for larger bandwidths and/or multiple transmit antennas as we will explain with more detail later in this section. One type of solutions is to use multiple antenna techniques for self-interference cancellation, which requires more than two antennas at each full-duplex node [8], [14]. Another solution cancels self-interference by taking advantage of antenna directionality [15].

Some work has shown that the channel capacity is likely to be doubled on a single hop link, while spatial reuse and asynchronous contention effects likely significantly undermine

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the actual benefit of full-duplex in a large scale mesh network [16]–[18]. Researchers at Stanford [19] use a design that combines analog signal inversion cancellation with digital cancellation and can reduce self-interference by up to 73dB for a 10 MHz OFDM signal. Rice university [20] has used off-the-shelf MIMO radios for full duplex and presented the experimental results of three self-interference cancellation mechanisms: Antenna Separation and Digital Cancellation (ASDC), Antenna Separation and Analog Cancellation (ASAC), and Antenna Separation, Analog and Digital Cancellation (ASADC). These mechanisms are a different mixture of analog and digital cancellations in narrow-band with a bandwidth of 625 KHz. They obtained a conclusion that if the self-interference is cancelled in the analog domain before the interfering signal reaches the receiver RF front-end, then the resulting full-duplex system can achieve rates higher than a half-duplex system with identical analog resources. Askar *et al.* employs an auxiliary transmit chain to create the cancellation signal, which is then injected at the receiver RF front-end by using a microstrip coupler [21]. Two methods are then proposed to calculate the self-interference cancellation signal. While the first method assumes the transmit chain is strictly linear, the second one additionally incorporates nonlinear effects, occurring especially in the RF power amplifier. Their experiment results show 50 dB of suppression by using the nonlinear method and under nonlinear system behavior, whereas the linear approach reports 47 dB of suppression under the same conditions. Some other full duplex wireless progress includes the design of a passive self-interference suppression node with three different passive suppression techniques: directional isolation, absorptive shielding, and cross polarization [22].

III. Half Duplex and Full Duplex Wireless

To highlight the unique features and benefits of full duplex wireless, we inspect three typical topologies by contrasting traditional half duplex to full duplex wireless.

The first case is a relay topology as shown in Figure 1(a) [23], where node R acts as a relay for the single flow of data being sent from source node S to destination node D. If node R can only operate in half duplex, then it would need to alternate between receiving from node S and forwarding to node D, as shown in the left pane of Figure 1(a). However, if node R can operate in In-Band Full Duplex (IBFD), then it can receive and forward simultaneously (over the same frequency band), as shown on the right pane of Figure 1(a). Thus, by operating in IBFD mode, the relay network can potentially double the spectral efficiency [24]–[26] (measured in bps/Hz) compared to the half duplex operation. Note that the IBFD relay network only requires the relay node operate in full duplex; neither the source nor the destination node is required to simultaneously transmit and receive.

Another scenario considered is a bidirectional topology as shown in Figure 1(b), where there are two data flows: node A sends data to node B, and node B also sends data to node A. If either node A or B only can operate in half duplex, then the communication from A to B cannot occur simultaneously with the communication from B to A, and the two communications

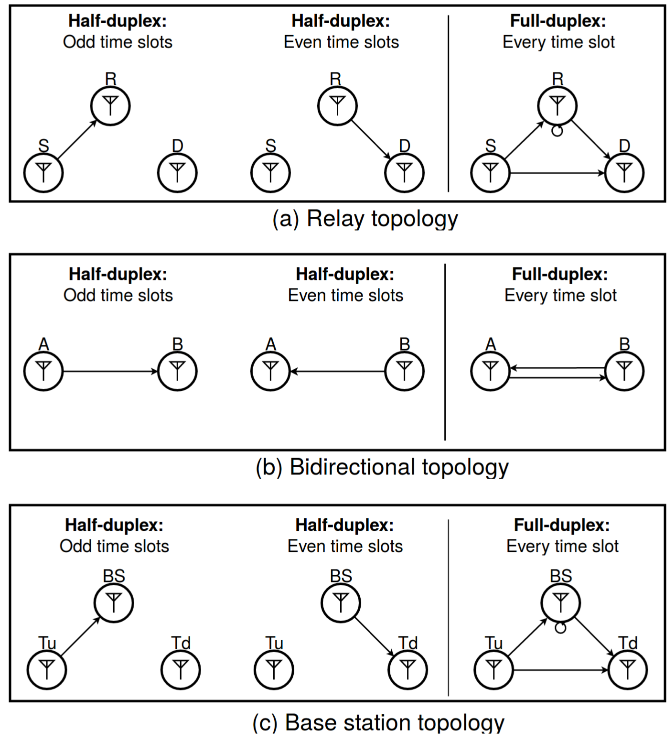

Fig. 1: Three example topologies that illustrate the implications of IBFD nodes at the network level. IBFD-capable nodes are in green, and IBFD-induced interference is in red.

must be performed over orthogonal time slots, as illustrated on the left pane of Figure 1(b). However, if both A and node B can support IBFD operation, then the communication from A to B can occur simultaneously with the communication from B to A, as on the right pane of Figure reffig:model(b). As a result, this potentially doubles the spectral efficiency of half duplex.

The last topology to consider is an infrastructure model with a base station as in Figure 1(c), where there are two data flows: node T_u sends data on the uplink to the base station BS, and the BS sends independent data on the downlink to node T_d . If the BS can only operate in half duplex, then it has to alternate between receiving from node T_u in one time slot and transmitting to node T_d in an orthogonal time slot, as shown on the left pane of Figure 1(b). However, if the BS can operate in IBFD, then it will be able to support simultaneous in-band uplink and downlink communications, potentially doubling the spectral efficiency as well. As in the relay topology, only the BS needs to support IBFD, not node T_u or T_d.

IV. Challenges and Problems

IBFD obviously has tremendous potentials to improve spectral efficiency. To enable IBFD in practice, however, we have to address a fundamental full duplex wireless problem–*signal self-interference* that occurs because its own transmitted signal of a node collides its received signal from others due to the simultaneous transmission and receiving in full duplex mode. It is extremely challenging to mitigate self-interference. For example, WiFi signals are transmitted at 20 dBm power, and the noise floor is around -90 dBm, which means the self-interference from the transmission has to be cancelled by 110 dB so as to be reduced to the noise floor and rendered as negligible [27]. Otherwise, the useful signal received from the others will be corrupted for correct decoding by the self-interference. This section inspects key elements that contribute to the harassment of self-interference.

A. Distortion of Original Signal

At the first glimpse, IBFD likely seems simple to accomplish. Theoretically, since the transmitted signal is known, self-interference can be easily remove by designing circuits and algorithms to subtract the known transmitted signal from the received signal mixture. The practice is however far more complicated. Referring to the concept block diagram of an RF transmitter on the Figure 2, every signal being transmitted has to be converted to analog and then influenced by complex environments, e.g. multiple-path. Meanwhile, a signal being received has to be converted to digital. As a result, each component in the chains that the received and transmitted signals pass through contributes to noises [19], distorting the original signal.

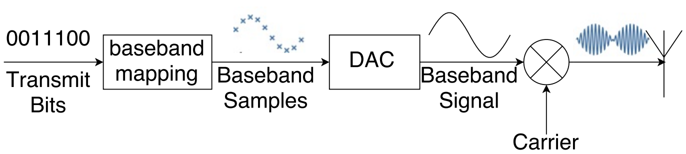

Fig. 2: Block diagram of an RF Transmitter

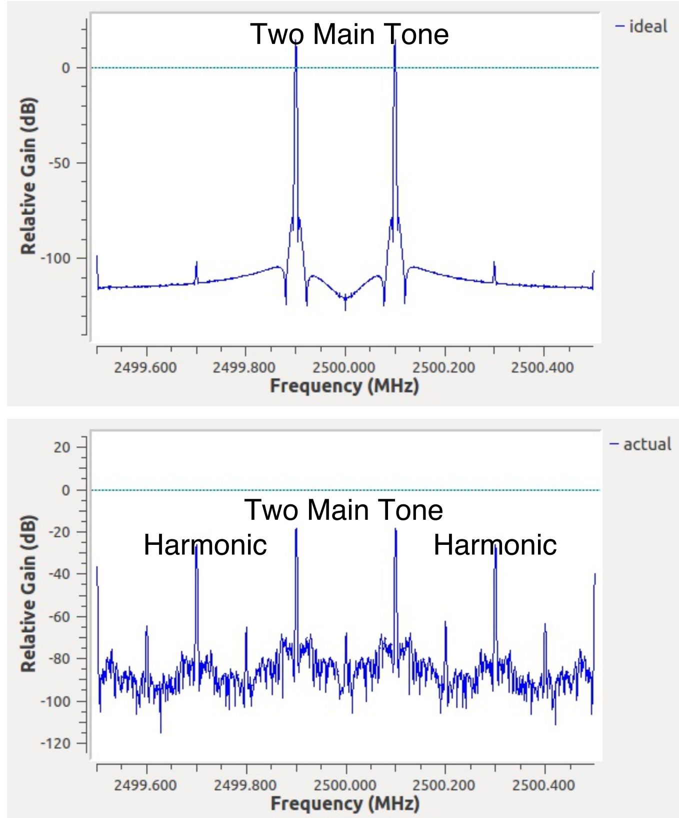

Fig. 3: What we think we are transmitting is on the top diagram, and what the radio actually transmits is at the bottorm diagram

An experiment has been performed to investigate the signal distortion issue. In the test, a USRP X310 node with two UBX daughter boards is used. Two tones selected in transmission are 2.4999GHz and 2.5001GHz, and the power is 20 dBm. Ideally, we expect to see only two transmitted tones at 2.4999GHz and 2.5001GHz as shown on the top diagram of Figure **??**. The actual transmitted signals however show very different distorted spectra as plotted at the bottom diagram of Figure **??**.

The components distorting original signal can be classified into three major categories [27]: linear component, non-liner component, and transmitter noise.

1) Linear Components: The linear components contributing to the self interference are from the regular propagation of the transmitted signal. They consist of both Line-of-Sight (LOS) and Non-LOS elements. In propragation, the transmitted signal arrive at its own receiver of a wireless node with different power attenuation and phase changes from various paths through reflection, diffraction and refraction in a particular environment. These are linear components because the received signal mixture can be written as a linear combination of different delayed and attenuated copies of the original signal. The signal mixture is normally represented by the formula below:

$$y(t) = \sum_i a_i(t)x(t - \tau_i(t)) \tag{1}$$

where $a_i(t)$ refers to the attenuation in the i-th path that depends on the SNR of the path, $\tau_i(t)$ is the propagation delay of the i-th path. This is graphically illustrated by the plot in Figure 4. As can be observed from the formula and the figure, the received linear component is only related to time delay or phase delay and amplitude attenuation, which is possible to result in the inter symbol interference(ISI) in two main tones.

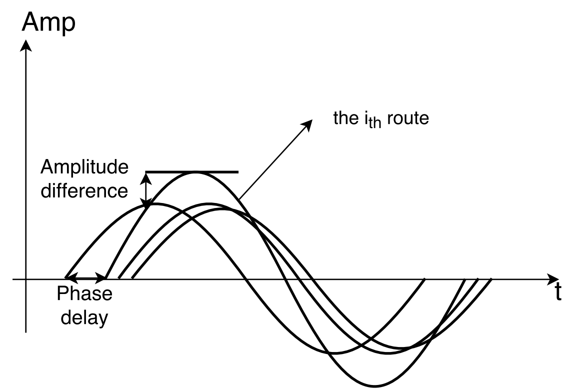

Fig. 4: The multi-path effect introduces linear component

2) Non-Linear Component: The non-linear components are resulted because of the imperfection of the radio circuits in wireless network interfaces, which takes an input signal x but creates an output that contains not only the signal x but also non-linear cubic and higher order elements such as x^3 and x^5. These high order signal elements have significant amount of content at frequencies close to the transmitted frequency, which correspond to all the other harmonics that lead to signal distortions occurring at equally spaced frequencies from the transmitted frequencies, as we can observe at the bottom digram on Figure 3. The spikes at frequencies of 2.4997GHz and 2.5003GHz, which are spaced 2 MHz apart on either side from the two transmitted tones 2.4999 GHz and 2.5001 GHz.

3) Transmitter Noise Components: The transmitter noise can be seen clearly on the sides of the two main tones in spectrum on Figure 3. Wireless normally has a noise power level of -90 dBm [28]. From Figure 3, however, the power at the side-bands is of -20 dBm, which is significantly higher than the normal noise level. This extra noise is resulted from the high power components in the radio transmitter such as power amplifiers [29]. In the radio literature, this is referred as broadband noise [30].

B. Residual Self-interference

It is intuitive to consider self-interference cancellation by subtracting its transmitted signal from its received signal mixture at an IBFD node. However, this cancellation solely can't reduce the self-interference enough. This approach to cancelling self-interference occurs in digital domain, which happens after the analog-to-digital converter (ADC) in the RF chain. It is the ADC dynamic range that leads to the problem called *residual self-interference* after the transmitted signal is subtracted from the received mixture. Suppose that the IBFD node has a 14-bit ADC with 11 effective bits (ENOB=11). Such an ADC yields an effective dynamic range of 6.02×(11-2) [31], corresponding to 54 dB. As a result, with such an ADC, even if the transmitted signal is subtracted from the received signal mixture in digital domain, the self-interference power can be reduced maximally by 54 dB, which still fall far behind the required cancellation of 110 dB in WiFi.

To reduce the self-interference more, some designs have made significant progress [32]. Even so, the best performance combining propagation cancellation, analog cancellation and digital cancellation can cancel 85 dB so far, which still leaves the residual self-interference of about 25 dB to reach the required 110 dB cancellation. To achieve full duplex wireless, one option is to increase the power of the received signal from others, but it must be extremely high ($>$ 45 dB), which would require two wireless nodes be closer than 5 m for such high SNRs [32], [33]. However, these designs were intended for low-power, narrow-band, fixed rate protocols such as Zigbee where self-interference cancellation of 85 dB is sufficient for full duplex. Unfortunately, board-band wireless such as WiFi demands much more cancellation of self-interference to meet the noise floor requirement.

V. INTERFERENCE CANCELLATION

Since the power of self-interference in full-duplex terminal is obtrusively high, it is easy to overwhelm the desired signal at the receiver and also to exceed the dynamic range of the receiver circuitry (e.g., ADC) [32], [34], [35]. Since its inception of full duplex wireless, many solutions have been proposed to cancel self-interference.

A. Propagation Cancellation

One type of solutions uses signal propagation properties for self-interference suppression. Generally, propagation suppression can be achieved in different ways, e.g, path loss, directional antennas, antenna placement, duplexer, transmit beamforming, etc. For example, some solutions [36], [37] suppress self-interference by enlarging the physical distance d between transmit and receive antennas because the received self-interference power p follows $p \propto \frac{1}{d}$, but this idea is problematic for small-size devices because there is no room for antenna deployment. Some solutions suggest that directional antennas be so equipped that the gain of transmit antennas is low in the direction of the receive antennas [38].

More recently, antenna placement solutions have been proposed to place two transmission antennas asymmetrically at d and $d+\frac{\lambda}{2}$ distance from the receive antenna, as shown on Figure 5, where λ is the wave length of the operation frequency [8], [39]–[41]. This placement of antennas allows the transmitted signals to have π out of phase and hence they cancel each other at the receive antenna. Antenna placement solutions seem effective, but have a few problems. The first issue is the waste of power in cancelling self-interference because another identical signal has to be transmitted from a second antenna. The second problem is that the performance highly depends on channel estimation. As in the experiment presented by Choi [8], the performance of asymmetrical antenna placement is extremely sensitive to the distance and amplitude deviations. In a bandwidth of 5 MHz, 1 mm distance mismatch can result in a power reduction to only 28.7 dB, while the perfect reduction is -60 dB. Meanwhile, 5% amplitude mismatch leads to at most -30 dB in power. Thirdly, antenna placement has impact on a large surrounding area, which is called *nulling area* where a wireless node wants to receive the signal from another node, but the received signal power will be lower than normal situation.

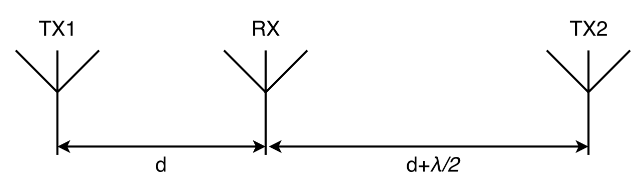

Fig. 5: Antenna cancellation with two transmit antennas at a full-duplex node

B. Analog Domain Cancellation

In addition to the propagation cancellation of the self-interference in the air, another category of self-interference cancellation occurs in the analog domain between antenna and ADC. Analog domain cancellation solutions commonly use gradient descent algorithms to adjust parameters such as delays and attenuators after antenna cancellation for less residual signal power [8], [19], [27].

Figure 6 shows a typical block diagram of analog cancellation. The RSSI represents the residual signal power after the self interference has been subtracted from the received signal through the Balun cancellation, which just simply inverses the transmit signal phase and then adds to the original signal to emulate the propagation cancellation [19]. As we can observe, QHx220 does not actually provide a variable delay. Instead, it takes the input signal from the Balun module and separates it into in-phase and quadrature components. The quadrature component has a fixed delay (τ) with respect to the in-phase component. It emulates a variable delay by controlling the attenuation of the in-phase and quadrature signals (g_i and g_q), then adds them to create an inversed-phase cancelling signal. By introducing a gradient descent algorithm, these parameters can be finely tuned for less residual signal energy.

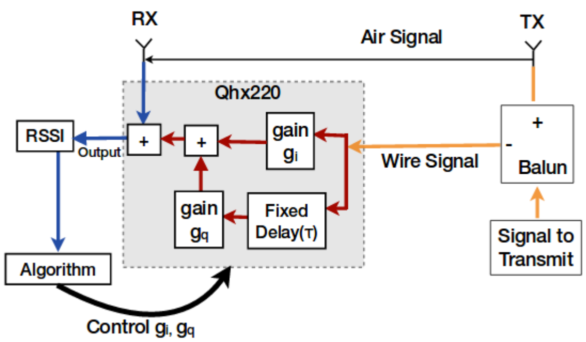

Fig. 6: Analog cancellation model [19]

Analog self-interference cancellation can be either channel aware or channel unaware. Channel unaware techniques aim to cancel only the LOS self-interference. The "passive suppression" techniques fall into this category [21], [38], [42]. Other the other hand, channel aware schemes consider all paths of self-interference. Examples include the "active cancellation" techniques [8], [19].

C. Digital Domain Cancellation

Digital domain cancellation aims to cancel self-interference after ADC. The advantage of self cancellation in digital domain is that the cancellation can be conducted as signal processing and easily. Because digital signals are what we can observe and process directly in computing components such as FPGA, microprocessor and even a general computer.

Since each digital transmitted symbol is exactly known, it is feasible to subtract the transmitted symbols from the received mixture symbols. However, because the self-interference symbols in the received mixture symbols have been somehow distorted in the propagation, namely they are not exactly the same as their original forms, it is necessary to estimate the analogy channel mode including propagation and analog circuit suppression for real-time full duplex wireless. One option of channel estimation is to perform channel probing with only one full duplex node at one time. With this only node, when it transmits probing symbols, it knows what expects to receive in digital domain. It then compares what is actually received with what expects to receive to learn the channel model. Bharadia *et al* use two known OFDM symbols at the start of the initial step, and they build the channel model as below [27]:

$$y_{init}[n] \quad = \quad \sum_{i=0}^{2k} x[n-k+i]h[k-i] + w[n] \qquad (2)$$

where $y_{init}[n]$ and $x[n]$ are respectively the n-th received probing symbol and transmitted probing symbol, $h[k], ..., h[-k+1]$ represent the attenuations applied by the channel to the transmitted signal, and $w[n]$ is the receiver noise floor. In this model, the received sample $y_{init}[n]$ at the moment n is formulated as a linear combination of up to k samples of the known transmitted signal $x[n]$ before and after the moment n. The parameter k is empirically chosen and is a function of the amount of memory in the channel. Therefore, their channel model in Equation (2) is a combined linear and non-causal function of the transmitted signal, because the symbols of the entire probing frame are also known.

To estimate the channel attenuation coefficients $h[\cdot]$, Equation (2) can be expressed specifically for the entire probing preamble as:

$$y_{init} = Ah + w \qquad (3)$$

where A is the matrix containing symbols transmitted from $-k$ to $n+k-1$.

$$A = \begin{bmatrix} x[-k] & \dots & x[0] & \dots & x[k-1] \\ x[1-k] & \dots & x[1] & \dots & x[k+1] \\ \dots & \dots & \dots & \dots & \dots \\ x[n-k] & \dots & x[n] & \dots & x[n+k-1] \end{bmatrix} \qquad (4)$$

Hence matrix A can be pre-computed, and y_{init} is the symbol received in the initial probing period. Then h can be estimated according to Equation (3).

After the channel mode is estimated, the next step is to apply the channel model to the known transmit signals in actual communications with others to generate cancelling digital symbols, which will be used to subtract the self-interference from the received signal mixture. Jain *et al.* uses an FIR filter implementing the estimate channel mode to generate the cancelling symbols in digital domain [19]. Denote a generated cancelling symbol as $y_e[n]$. Then $y_e[n]$ is subtracted from $y[n]$ that represents the received symbol mixture containing both the self interference information as well as the valuable information from other nodes in communication [20]. As a result, the symbols after digital cancellation can be represented as below:

$$y_e[n] \quad = \quad \sum_{i=0}^{2k} x[n-k+i]h[k-i] \qquad (5)$$

$$y_d[n] \quad = \quad y[n] - y_e[n] \qquad (6)$$

where $x[n]$ is a signal that a full duplex node transmits at itself. $y_d[n]$ is the desired symbol after digital self-interference.

VI. MAC Layer Protocol Design

Traditional wireless MACs such as CSMA/CA were designed for half duplex wireless systems. Some classic MAC problems in half duplex wireless systems include exposed terminal problem, hidden terminal problem, fairness issue and loss of throughput and high end-to-end delay in multi-hop wireless networks. With self-interference cancelled at the PHY layer, however, full duplex wireless systems require new MAC protocols. With new full duplex MAC protocols, indeed, the problems in half duplex wireless MACs can be solved or at least mitigated to some extent.

A. *Exposed Terminal Problem*

With CSMA/CA in half duplex systems, a wireless node is required to sense if the channel is idle before it can send any frame. Exposed terminal problem refers to the situation that, when node A is within the carrier sense range of node B that is transmitting, node A explains the channel is busy and will hold off its transmission. In this particular situation, even if node A transmits, there will actually be no issue because neither node A or B receives, but the carrier sense required by CSMA/CA blocks the parallel transmissions.

Obviously, in an in-band full duplex wireless system, each node can simultaneously transmit and receive on one channel. Therefore even if node A is transmitting, node B does not need to detect if the channel is busy or not because it can just transmit to any node if their transmissions do not collide on this node. Figure 7 shows the difference between these two modes.

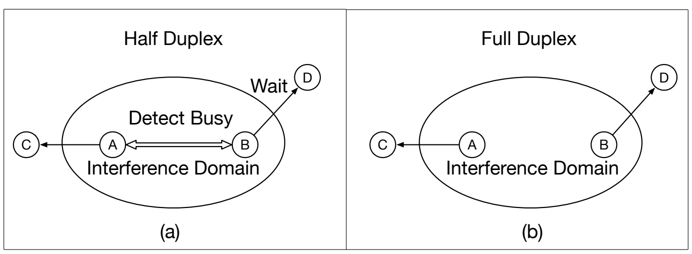

Fig. 7: Exposed terminal problem in half duplex and full duplex modes

B. *Hidden Terminal Problem*

Hidden terminal problem occurs when two nodes are out of the carrier sense range to each other and their simultaneous transmissions result in a collision at a node that is within both of their signal coverages, as Figure 8 shows.

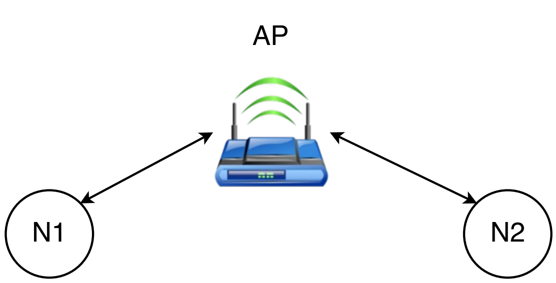

Fig. 8: Hidden terminal problem when N1 and N2 is hidden to each other

Hidden terminal problem can be solved in full duplex wireless [8], [19]. With the capability of in-band full duplex, as soon as N1 starts transmitting data to the AP, the AP starts transmitting data back to N1 simultaneously. N2 hears the signal of the AP and delays its transmission, thereby avoiding a collision to the AP. If the AP does not have any packets to send back to N1, it can simply send a nonsense busy tone to inform hidden terminals e.g. N2, or repeat whatever it hears as the busy tone. As a result, no RTS/CTS is needed to avoid the hidden terminal problem.

However, transmitting a busy tone to avoid the hidden terminal problem is wasteful in terms of energy consumption. Kim, Lee and Hong propose a new FD-MAC protocol based on RTS/CTS [7]. In the FD-MAC protocol, each node listens to channel for a fixed period of time during DIFS (distributed inter frame space in IEEE 802.11). If the channel is idle during the DIFS, the source node S starts a random backoff timer. The size of the backoff timer is randomly chosen from the contention window. Referring to Figure 9, when the backoff expires, the S transmits an RTS frame to the destination. Upon the reception of the RTS frame, the destination node D responds with a CTS frame to S. When other nodes in the network hear either RTS or CTS, they defer the frame transmission until the packet transmission is finished. During the primary packet transmission, D can also transmit a frame to S, which is the secondary packet transmission, in full duplex mode. Because other nodes would defer when RTS packets they received, channel from destination to source node is implicitly reserved as well. FD-MAC basically adopts the current CSMA/CA protocol in IEEE 802.11 and introduces the full duplex only in the transmission of data frame. FD-MAC has problems that, when there is no valid data to transmit from D to S, the channel is still reserved, which works back as the current CSMA/CA in half duplex mode. Another problem of FD-MAC is the retainment of the exposed terminal problem. As in Figure 9, even if H wants to transmit package to A, it has to wait for the session of S to D to finish.

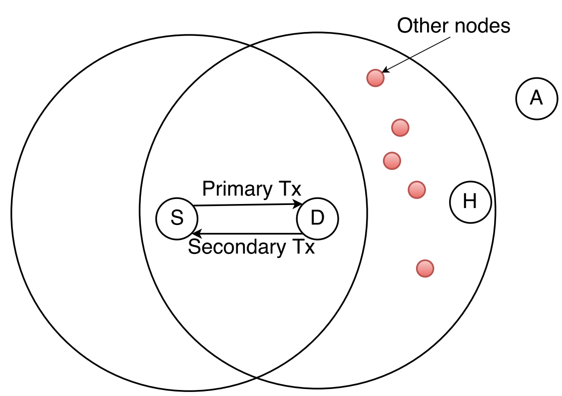

Fig. 9: FD-MAC protocol based on RTS/CTS

C. *Fairness Issue*

One problem in traditional half duplex wireless systems is fairness. When a wireless network has a congested node, the network throughput in regular MAC operation is severely affected. Figure 10 shows the fairness issue [19]. An access point R1 connects to three clients, and all clients are within the carrier sense range of each other. If each node has a bidirectional UDP connection to R1, then there six active UDP flows.

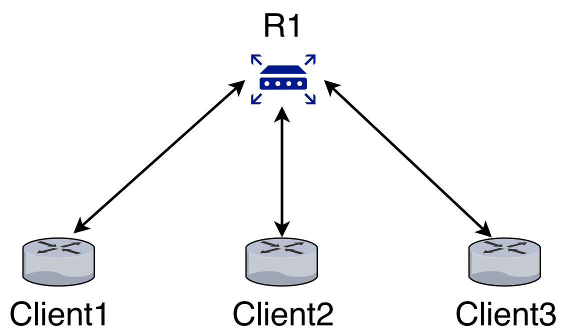

Fig. 10: Congested node R impact on less throughput in regular MAC

In half duplex wireless mode, when the traffic is saturated, indicating that the channel cannot bear more traffic, then R1 gets the same share of the channel as all other nodes. However, R1 potentially has three times of traffic as any other node, because it is sending downstream traffic to all three clients. Consequently downstream flows get an unfairly low share of the channel when the network is saturated. Moreover, if R1 have n clients with same carrier sense range, the AP's throughput to all nodes is only $1/(n+1)$ [8]. The same problem also occurs in a star topology of multi-hop networks.

In in-band full duplex systems, however, R1 can transmit and receive at the same time. Therefore, for each transmission from any client, R1 is able to send a downstream packet to that client, thus achieving fairness between upstream and downstream flows.

VII. Full Duplex Performance

With various self-interference solutions and MAC protocols presented in above sections, this section summarizes the performance improvement of the full duplex wireless solutions that have been proposed so far.

A. Self-interference Cancellation

Among those self-interference cancellation designs, this paper choose three of them, Stanford [27], Balun [19] and Rice [20], to compare and show if they can cancel the self-interference to the noise floor. Their self-interference cancellation performance is shown in Figure 11. The left plot shows transmission power on x axis and cancelled power on y axis, while . As we can observe, along with the increase of transmission power, Stanford solution has better performance in cancelling self-interference with increasing cancelled power on the y axis, while the other two solutions have rather invariant results in cancellation. Stanford solution can cancel 110 dB self-interference with a 20 dBm TX power. The right plot of Figure 11 shows the performance of noise floor when those three designs are tested. Stanford solution can cancel self-interference to noise floor even though the TX power increases, while the other two solutions fail to do so.

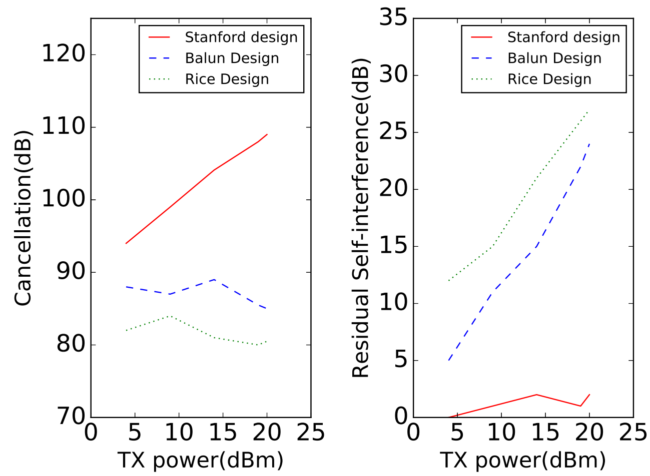

Fig. 11: Cancellation vs TX power for different cancellation techniques with WiFi signal

B. PHY Layer and MAC Layer Performance

1) PHY Layer Performance: Theoretically, full duplex wireless can improve spectrum efficiency and double throughput. To evaluate the actual performance of the full duplex wireless physical layer in practice, experiment have been performed by the team of Stanford solution [27] using two WARP devices to send batches of 1,000 packets in both full duplex and half duplex modes at a serial of different locations. They have collected the throughputs at these locations, and the throughputs CDF results are plotted in Figure 12. As we can observe from the data on the figure, their design of full duplex wireless achieves a median throughput gain of 187% over the standard half duplex mode, at the cost of a small SNR loss due to a small amount of residual self-interference.

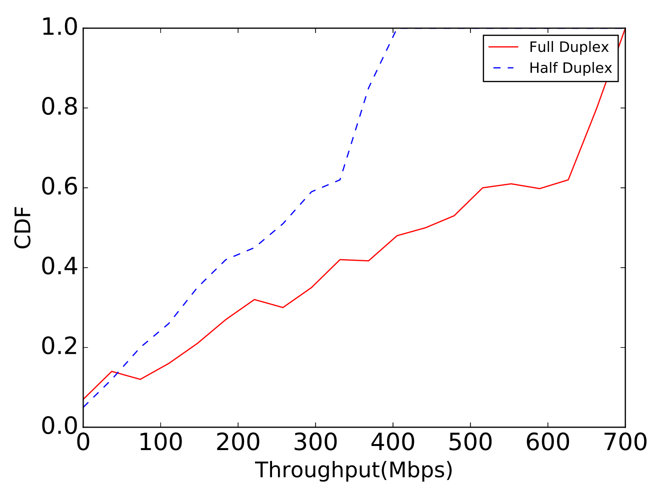

Fig. 12: CDF of half duplex and full duplex bidirectional transmissions

2) MAC Layer Performance: Since full duplex wireless has significant impacts on hidden terminal, exposed terminal and fairness problems in traditional half duplex MAC protocols, it is of utmost interest to evaluate the MAC layer performance of full duplex wireless. Jain *et al.* has conducted such experiments [19]. They use two wireless nodes that are hidden to each other as in the topology shown on Figure 8. Both nodes attempt to send UDP packets to the AP with the full duplex MAC protocol or the half duplex CSMA/CA, but no downstream data flow from the AP to nodes. Obviously, the hidden terminal effect will result in packet collision at the AP. The test results are shown in Figure 13, where two metrics are plotted: throughput on the left vertical axis and packet reception ratio (PRR) on the right axis, and the horizontal axis shows the UPD data traffic bit rates from the nodes to the AP in the test.

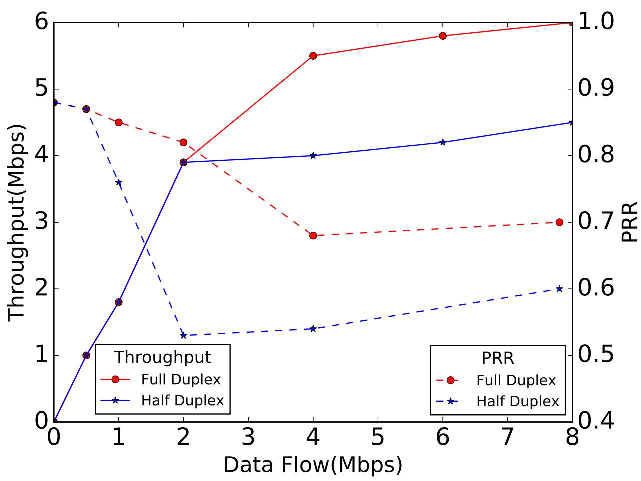

Fig. 13: MAC layer performance with hidden terminals

As we can observe from the figure, full duplex wireless obviously outperforms half duplex wireless on both the throughput and PRR performance. As the traffic bit rate increases, full duplex wireless quickly shows its strength with better throughput and PRR. This is because the busy tone mentioned before is useful to prevent collisions that however aggravates in half duplex wireless as the traffic becomes heavier. At the traffic rate of 2 Mbps, although the PRR of half duplex MAC drops to 52.7%, full duplex MAC maintains a ratio of 83.4%. Another interesting observation is that, when the traffic rate of each flow is high, e.g. 7 Mbps, the full duplex wireless does not result in a throughput close to the aggregate traffic rate 14 Mbps as normally expected. This is because the traffic is unidirectional from the nodes to the AP, full duplex at the AP does not help receiving simultaneous incoming traffic flows because it can only receive alternatively from one node at one time.

VIII. Conclusion

This paper reviews the research background and progress of the full duplex wireless. The research problems are analyzed and the opportunities are highlighted. A summary of the latest relevant research is provided, including self-interference cancellation, physical layer and MAC layer solutions. At the end, the performance evaluations of various solutions are presented.

IX. Acknowledgement

This material is based upon work supported by the National Science Foundation under Grant No. ECCS#1408165.

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