Fundamental Survey of Full Duplex Wireless Communication

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Introduction

In this survey, we have discussed about the basic concept of in-band full-duplex (IBFD) wireless communication. We have given emphasis on the Medium Access Control (MAC) design for IBFD wireless communication. This survey has two sections. First section includes the fundamental study and second section includes a example of IBFD MAC design.

Section-1:

- Concept of In-band Full-duplex (IBFD) wireless communication and MAC design.

Section-2:

- An Example of a IBFD Medium Access Control Design.

Section-1

Outline of this section

- Introduction
- Basics of full-duplex
- Advantages of in-band full-duplex (IBFD)
- Disadvantages of IBFD
- Antenna Configuration for IBFD
- Transmission modes in IBFD system
- Basic concept of MAC design
- Challenges of MAC design for IBFD

1.1 Introduction: **1/2**

- **Why Faster WLAN is Needed:**

Faster WLAN is required as:

- Network traffic is increasing very rapidly.

- A lot of applications and services are available now. Many users want to use more applications at the same time.

Fig-1. Future trend for Mobile traffic in exabytes (EB) per month

1.1 Introduction: 2/2

- **Current Technologies for Faster WLAN:**

To meet the challenges of increasing traffic in future, we need faster WLAN. The state-of-the-art techniques for faster WLAN include:

- Full Duplex (FD)
- Interference Cancellation
- Superposition Coding
- Multiple Input Multiple Output (MIMO), etc.

1.2 Basics of Full-Duplex: 1/2

In these tutorial, the concept of Full-Duplex (FD) technologies as well as medium access control design will be described sequentially.

Traditional Full-duplex:
The stations can transmit and receive simultaneously. But, this is done by two conventional way:

i. Time Division Duplexing (TDD)
ii. Frequency Division Duplexing (FDD)

- So, traditional full-duplex (FD) is performed either in same frequency and different timeslot for transmit and receive, or same time and different frequency for transmit and receive simultaneously.

1.2 Basics of Full-Duplex: 2/2

- **In-band Full-duplex:**
- Unlike traditional full-duplex (FD), in-band FD communication is performed by using same time as well as same frequency for transmit and receive simultaneously.
- But for doing this FD successfully, we need to eliminate the self interference.
- So, self interference cancellation technique (SIC) is very important here.

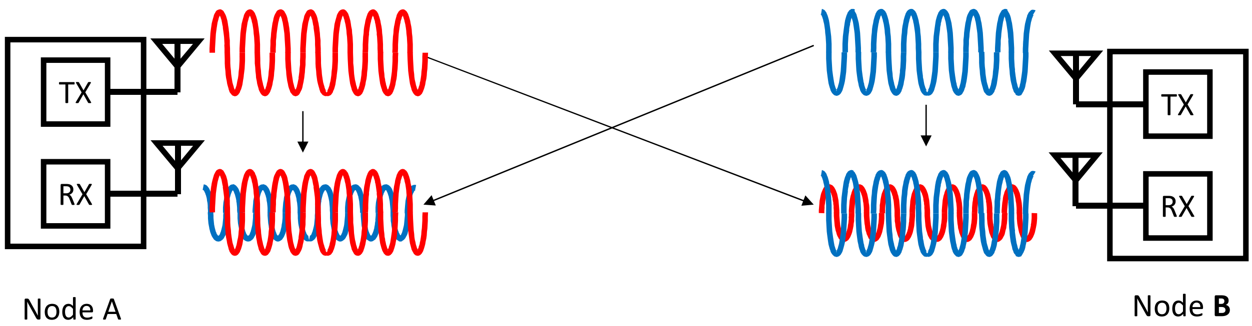


Fig-2. FD wireless transmission

1.3 Advantages of In-band FD: 1/2

The main advantages of in-band FD (IBFD) system can be summarized as follows:

- **Can double throughput gain:**
  In-band FD (IBFD) transmission can utilize the time and frequency resources properly. As a result, it is theoretically possible to double the link capacity as compared to HD transmission [1],[2].

- **Can reduce feedback delay:**
  Reception of feedback signaling (such as control information, channel state information (CSI) feedback, acknowledge (ACK) signals, resource allocation information, etc.) during data signal transmission enables shorter air interface latency in feedback information [2].

1.3 Advantages of In-band FD: 2/2

- **Can reduce end-to-end delay:**
  In relay systems, relay nodes with IBFD transmission can reduce end-to-end delay because the relay node simultaneously receives data from a source node and transmits data to a destination node.

- **Can suppress hidden terminal problem:**
  Simultaneous listening and sensing can be performed on a frequency band while the signals are being transmitted. So, each node can decide whether or not the other nodes are transmitting signals and thus collision can be avoided.

1.4 Disadvantages of In-band FD:

The major disadvantages of IBFD can be summarized as below:

- **Self Interference:**
  Simultaneous transmission and reception in a single frequency band can cause the transmitted signals to loop back to their receive antennas. It will create self interference (SI). Proper self interference cancellation techniques should be used to minimize this self interference.

- **Imperfect interference cancellation:**
  In practical environments, the SI can not be perfectly canceled for a variety of reasons, such as the non-linearity of hardware components in the RF chain (the SI power is beyond the feasible range), estimation errors on the self-channel and the received SI signal (various reflected interferences), and incompleteness of various cancellation techniques [1].

- **Inter-user interference:**
  As the FD nodes transmit and receive simultaneously, it will create inter user interference. The number of inter-user interferers increases by almost a factor of two and the aggregate interference at a node increases as well.

1.5 Antenna Configuration for IBFD:

As IBFD requires in-band operation for transmitting and receiving radio frequency (RF) chains, the conventional duplexers cannot separate these two RF transmissions. So, IBFD can be performed by using the following antenna configurations:

- Shared Antenna [3]: In shared antenna configuration, a single antenna is used for simultaneous in-band transmission and reception by using a three-port circulator. Ideally, a circulator prevents the leakage signals from the transmit RF chain to the receive RF chain. But, in real case, the transmit signal causes also causes interference to the received signals.

- Separated Antenna [3]: In this configuration, there are separate antennas for transmission and reception. This division of spatial resources, however, introduces a trade-off. As such, a fair comparison between HD and FD transmission should consider the exact number of RF antennas required to establish FD transmission.

1.6 Transmission Modes in IBFD System: 1/2

- **Half-Duplex:** In half-duplex (HD) mode the transmission is performed in a single direction (Fig. 3(a)).

- **Bi-directional FD (BFD):** In this case, two node transmit signal to each other and thus receive signal simultaneously. That means two node transmit and receive simultaneously (Fig. 3(b)).

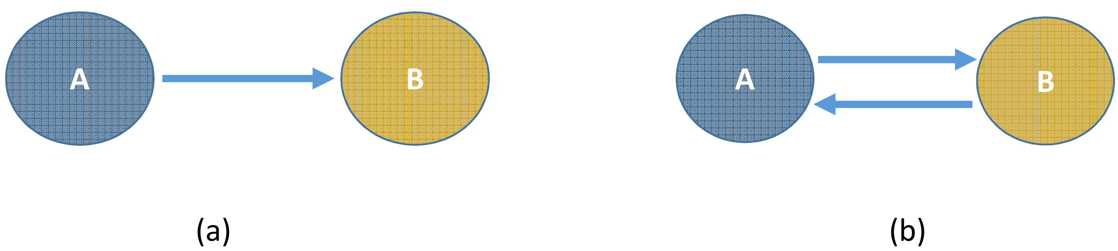


Fig-3. FD transmission mode: (a) HD mode and (b) BFD mode

1.6 Transmission Modes in IBFD System: 2/2

- **Relay FD (RFD):** In RFD system, a FD node transmits signal to one node while receiving from another one. As in Fig. 4, node C transmits to node A and A transmits to node B simultaneously. Here, node A is in FD mode, however node B and C are in HD mode.

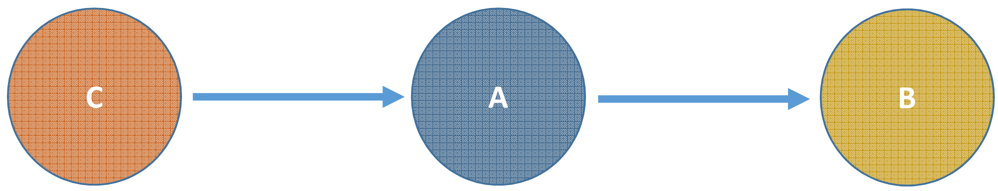


Fig-4. FD transmission mode: Relay mode

1.7 Basic Concept of MAC design: 1/8

- In OSI (Open Systems Interconnection) terms, higher-layer protocols (layer 3 and above) are independent of network architecture and are applicable to LANs, MANs, and WANs. Thus, a discussion of LAN protocols is concerned principally with lower layers of the OSI model.
- This figure relates the IEEE LAN protocols to the OSI architecture.

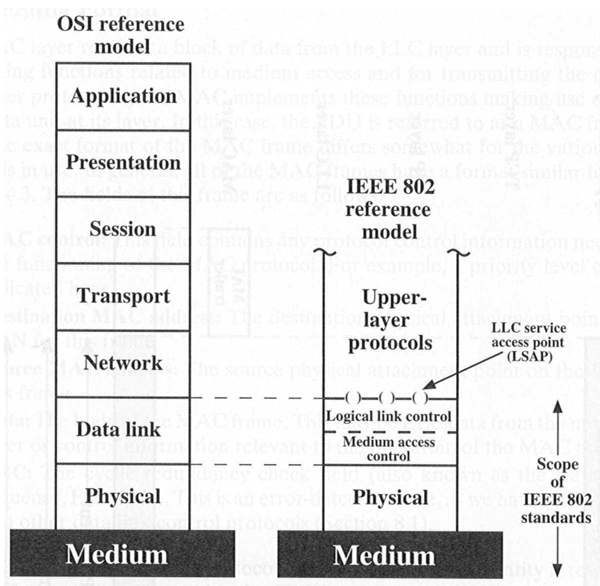


Fig-5. IEEE 802 Protocol Layers Compared to OSI Model

1.7 Basic Concept of MAC design:

- So the 2nd layer (Data link layer) has two sub-layer:
  (i) Logical Link Control (LLC) and (ii) Medium Access Control (MAC).

- The Logical Link Control (LLC) is responsible for error and flow control.

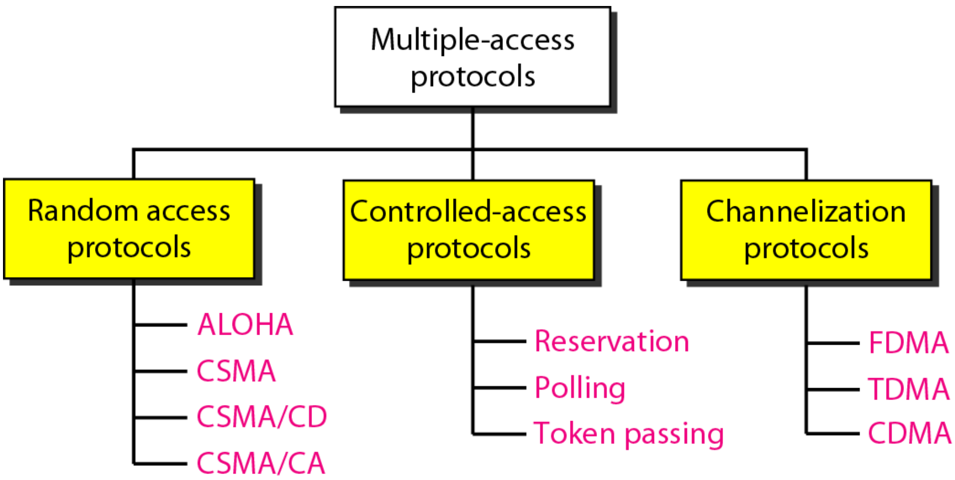
- On the other hand, MAC layer is responsible for framing and MAC address and Multiple Access Control.

- MAC layer sets the rules how the medium will be accessed by the users.

1.7 Basic Concept of MAC design:

➢ **Taxonomy of Multiple-Access Protocols**

- To understand the MAC design, one should have the basic concept of multiple access control. The taxonomy of multiple access protocols can be shown by the following chart.



Source:
Behrouz A. Forouzan, "Data Communications and Networking," 4th edition.

1.7 Basic Concept of MAC design:

- **Taxonomy of Multiple-Access Protocols**

Random Access (or contention) Protocols:

- In this type of protocols, no station is superior to another station and none is assigned the control over another.
- A station with a frame to be transmitted can use the link directly based on a procedure defined by the protocol to make a decision on whether or not to send data.
- There are a number of protocols in this category. However, as Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) is widely used in wireless communication, we will discuss briefly about CSMA/CA.

Source:
Behrouz A. Forouzan, "Data Communications and Networking," 4th edition.

1.7 Basic Concept of MAC design:

- **CSMA Protocol**

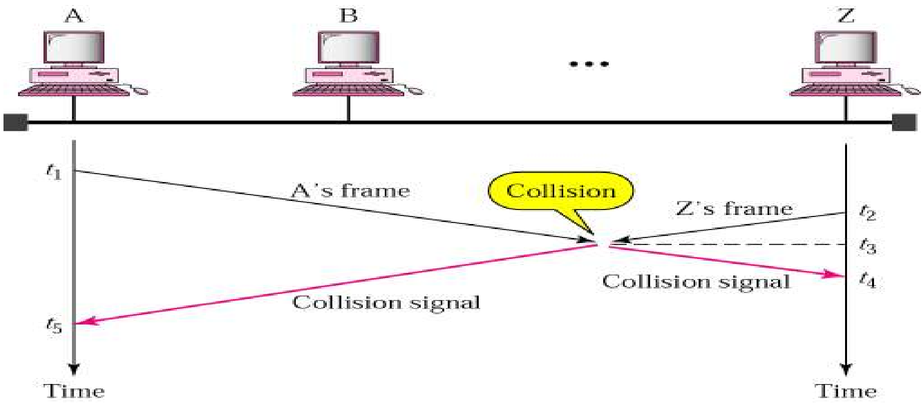
- By listening before transmitting, stations try to reduce the vulnerability period to one propagation delay. This is the basis of CSMA (Kleinrock and Tobagi, UCLA, 1975).
- If a frame was sent by a station, All stations knows immediately so they can wait before start sending
- A station with frames to be sent, should sense the medium to check the presence of another transmission (carrier) before it starts its own transmission.
- This can reduce the possibility of collision but it cannot eliminate it.

Source:
Behrouz A. Forouzan, "Data Communications and Networking," 4th edition.

1.7 Basic Concept of MAC design:

➢ CSMA Protocol

- However, collision can still be occurred when more than one station begin transmitting within a short time (the propagation time period) as shown in the following figure.



Source:
Behrouz A. Forouzan, "Data Communications and Networking," 4th edition.

1.7 Basic Concept of MAC design:

➢ CSMA / CA Protocol

- CSMA / CA protocol is proposed to avoid collision as well as to avoid hidden and exposed terminal problem. In general, CSMA / CA works according to the following way:
  - It uses four-frame exchange for better reliability.
  - Source transmit a Request to Send (RTS) frame to destination.
  - Destination responds with Clear to Send (CTS).
  - After receiving CTS, source transmits data
  - Destination responds with ACK, after receiving data successfully.

1.7 Basic Concept of MAC design:

➢ CSMA / CA Protocol

- So CSMA / CA protocol has following advantages:
  - RTS alerts all stations within the range of the source. As a result those stations do not start their transmission.
  - CTS alerts all stations within the range of destination. Similarly, those stations also do not start their transmission.
  - As a result of RTS and CTS, the collision is reduced significantly.
  - RTS/CTS exchange is required function of MAC but may be disabled, if required.

1.8 Challenges of MAC Design for IBFD:

i. Inter-user Interference:

- Here, suppose Alice sends RTS to AP (FD-AP) first and then AP takes decision to send data to Bob while receiving data from Alice.
- If Alice and Bob are close to each other, the packets from Alice will interfere with the packets from AP at Bob, which creates inter-user interference problem.
- The first one is primary transmission and second one is secondary transmission. So, Alice is primary transmitter (PT) and Bob is secondary receiver (SR). However, the access point is working as both primary receiver and secondary transmitter (PR/ST).

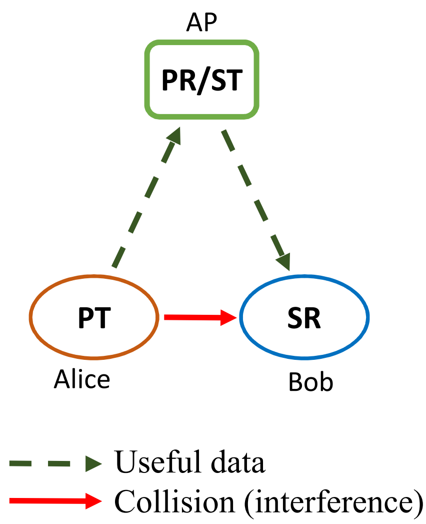


Fig-6. Inter user interference in FD-WLAN

1.8 Challenges of MAC Design for IBFD:

ii. Selecting FD Transmission Modes and Nodes:

- In wireless networks, clients can operate in any of the FD transmission modes that are illustrated in section 6. Hence, selecting a set of clients and an FD transmission mode is a vital issue to maximize the overall utility of FD transmission.

- The basic approaches that are currently used in FD-MAC protocols to select proper clients and modes for FD transmission are shared random backoff, header snooping, and request-to-send (RTS)/ clear-to-send (CTS) mechanisms [3].

1.8 Challenges of MAC Design for IBFD:

iii. Hidden Node Problem:

- In practical case, the primary and secondary transmitted packets may have different packet lengths. Therefore, the transmission of all nodes will not finish at the same time. As a result, relying only on FD data transmission (even in case if BFD mode) does not completely solve the hidden node problem.

- The hidden node problem in FD transmissions due to asymmetric data traffic at the transmitter and the receiver can be referred to as the residual hidden node problem [3].

- However, the node that finishes data transmission earlier can solve this problem by transmitting busy tone signals until the other node completes its transmission [5].

1.8 Challenges of MAC Design for IBFD:

iv. Deafness in Directional Antennas:

- If directional antennas are used in FD systems, neighboring nodes around the primary transmitter and secondary transmitter unable to detect these transmissions. This scenario is known as the deafness problem in directional transmission [3, 5].

- Due to the deafness problem, the neighboring nodes try to access the channel assuming that the channel is available for their transmission. This will end up with a collision in the ongoing transmission.

- To minimize this problem, a centralized MAC protocol can be used, as the central coordinator knows the locations of its registered nodes and their corresponding transmission directions.

Section-2

An Example of a IBFD Medium Access Control Design

2.1 Introduction:

In this section, we will describe briefly a MAC design for IBFD, which is published in IEEE transaction of Wireless Communication. This is a CSMA/CA (carrier sensed multiple access with collision avoidance) based MAC protocol. From this discussion, we will get an idea how to design a MAC protocol for in-band FD wireless communication. The information of the paper that will be discussed is given below:

- **Title:**

"Power-Controlled Medium Access Control Protocol for Full-Duplex WiFi Networks"

- **Authors:**

W. Choi, H. Lim and A. Sabharwal

- **Journal:**

IEEE Transactions on Wireless Communications
Volume: 14, Issue: 7, pp. 3601 - 3613, 2015.

2.2 Main contribution of the paper:

- This paper proposed a MAC protocol to manage inter-client interference in a wireless network.

- Here the network consists of an FD-AP and some half-duplex clients.

- They uses power control mechanism and distributed selection to manage inter-clients interference.

- Firstly, a RSSB (received signal strength based) back-off mechanism is proposed to provide a higher reception opportunity to the client with a low inter- client interference.

- Secondly, the transmit powers of the AP and transmitter are adjusted to minimize inter-user interference, which is called power controlled MAC (PocMAC).

2.3 Description of PoCMAC: 1/8

1) *Frame structures*:

- PoCMAC uses five types of control frames and two types of DATA frame headers, as shown in Fig. 10 and 11.
- The five control frames are:
  RTS, CTS-Uplink (CTS-U), CTS-Downlink (CTS-D), ACK-Downlink (ACK-D), and ACK-Uplink (ACK-U),
- The two types of DATA frame headers are:
  The header of the AP (HA) and
  The header of the client (HC)

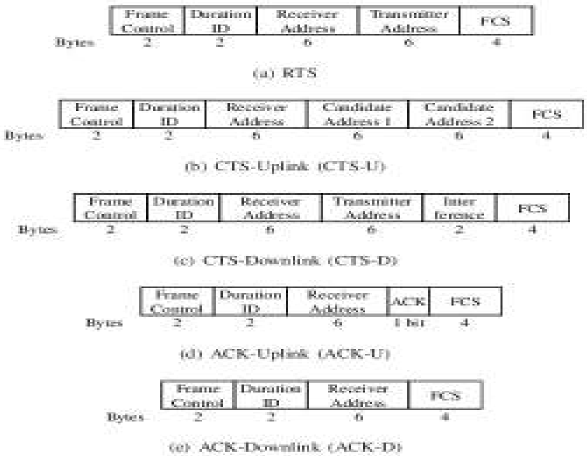


Fig-10. Control frame structure.

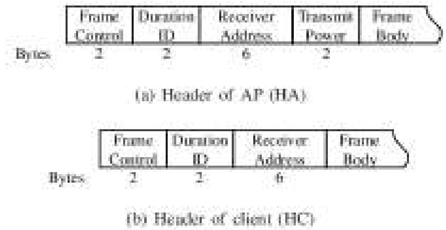


Fig-11. Header of data frame for AP and client.

2.3 Description of PoCMAC: 2/8

1) *Frame structures*:

- The CTS-U is transmitted by the AP after it receives an RTS from a client. In addition, using the CTS-U, the AP informs the candidate clients that it wants to transmit the DATA frame.
- The number of RX candidates that can be listed in the CTS-U frame is set to M. But here, it is only 2.
- The CTS-D frame is transmitted by the candidate client that wins the RSSB contention after the AP broadcasts a CTS-U frame.
- CTS-D also includes inter-client interference information, which is the received power of the RTS from the TX. If the RX cannot overhear the RTS from TX and cannot measure the signal strength, that field is filled with zeroes.

2.3 Description of PoCMAC: 3/8

2) Proposed PoCMAC:

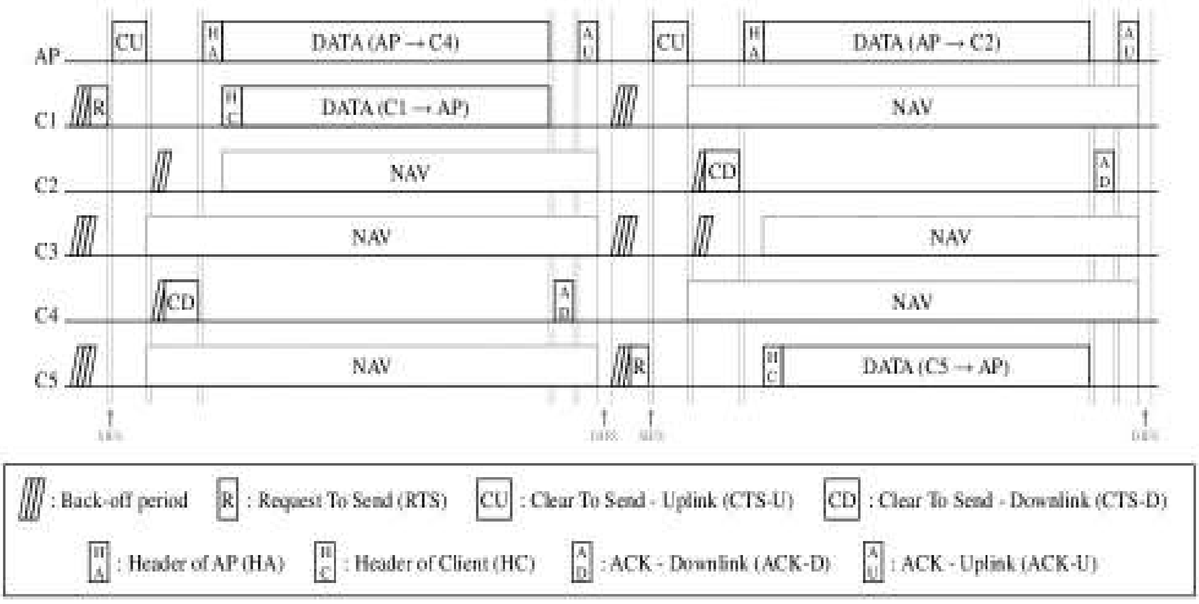


Fig-12. Operation example of the full-duplex AP and clients.
(1st transmission period: C1 - TX, C4 - RX / 2nd transmission period: C5 - TX, C2 - RX).

2.3 Description of PoCMAC: 4/8

2) Proposed PoCMAC:

- **TX side**

(1) All clients that want to transmit a DATA frame perform a back-off mechanism.

(2) The client that wins in back-off mechanism transmits an RTS frame to the AP and waits for a CTS-U from the AP.

(3) After receiving CTS-U from AP, TX waits for the HA of the DATA frame and others set network allocation vector (NAV).

(4) As soon as the TX receives the HA of the DATA frame from the AP, it starts to send uplink DATA with the transmit power specified in the received HA frame.

(5) After completing data transmission, the TX waits for an ACK-U frame from the AP.

(6) If the acknowledgement bit of the ACK-U frame is ‘1’, the TX can verify that the transmission was successful, and then return to the initial state.

(7) Otherwise, the TX returns to the initial state for retransmission.

2.3 Description of PoCMAC: 5/8

2) *Proposed PoCMAC*:

- **RX side**

(1) All clients that do not want to transmit a DATA frame to the AP, or that lose the contention, continue to overhear the RTS frame transmitted from other clients or wait for a CTS-U frame from the AP.

(2) After the clients overhear the CTS-U frame from the AP, they can identify the clients that are nominated as the RX candidates.

(3) If the client is one of the candidates for the RX, it performs the RSSB contention mechanism. Otherwise, it sets the NAV.

(4) The client that wins the contention among the candidates transmits a CTS-D frame, including the information on the inter-client interference from the TX, and waits for the HA of the DATA frame.

2.3 Description of PoCMAC: 6/8

2) *Proposed PoCMAC*:

- **RX side**

(5) If the client that transmitted the CTS-D frame receives the HA frame of the DATA frame, the client is considered to be the RX and starts the downlink DATA reception.

(6) If the downlink DATA reception is successful, the RX transmits an ACK-D frame to the AP. Otherwise not.

(7) After hearing an ACK-U from the AP, the RX returns to the initial state.

2.3 Description of PoCMAC: 7/8

2) *Proposed PoCMAC*:

- **AP side**

(1) The AP waits for an RTS frame from clients.

(2) After receiving the RTS, the AP transmits a CTS-U including the address of the TX and the addresses of the RX candidates to which the AP wants to transmit the DATA and waits for a CTS-D.

(3) After receiving the CTS-D, the AP can calculate the optimal transmit powers for the AP and TX; then, it starts the transmission of HA, which includes the transmit power for the TX.

(4) After transmitting the HA and stabilizing the interference nulling, the AP continues the downlink DATA transmission to the RX and starts the uplink DATA reception from the TX.

2.3 Description of PoCMAC: 8/8

2) *Proposed PoCMAC*:

- **AP side**

(5) After transmitting and receiving the DATA frames simultaneously, the AP waits for an ACK-D from the RX.

(6) If the ACK-D frame is received, the AP can determine that the downlink DATA transmission was successful, and then, it transmits an ACK-U with acknowledgement bit ‘1’.

(7) Otherwise, the AP determines that the downlink DATA transmission has failed, and then, it transmits the ACK-U frame with acknowledgement bit ‘0’ .

(8) After transmitting the ACK-U frame, the AP returns to the initial state.

2.4 Performance Evaluation: 1/3

The performance of the proposed PocMAC is performed by following way:

- The simulation is done by MATLAB.
- SDR (software defined radio) based evaluation is performed.
- The comparison is performed between PoCMAC and CSMA/CA based half-duplex scheme.

For the simplicity, only the simulation result by MATLAB has been presented here.

2.4 Performance Evaluation: 2/3

Simulation for Average Throughput

- They consider a single-cell system with an AP having full- duplex capability and its associated clients with backlogged user datagram protocol (UDP) packets.
- The transmission rates are set to 6Mbps for the control frames and 54 Mbps for the DATA frames.
- The simulation parameters are shown in Table-1.

TABLE I
PARAMETERS USED FOR PERFORMANCE EVALUATION

System Parameters			
RTS	160 bits	CTS	112 bits
CTS-U	176 bits	CTS-D	208 bits
ACK-U	113 bits	ACK-D	112 bits
ACK	112 bits	Payload	1500 bytes
HA	128 bits	HC	112 bits
DIFS	28 μs	SIFS	10 μs
CW_{min}	31	P_{max}	5 dBm
ω_α	16	ω_β	2
Basic rate	6 Mbps	Data rate	54 Mbps
SINR threshold	6 dB	Background noise	-70 dBm

Fig-15. $SINR_{Uplink}$ and $SINR_{Downlink}$ with respect to the suppression level of self-interference cancellation when the angle between the TX and the RX is 90◦.

2.4 Performance Evaluation: 3/3

Simulation for Average Throughput

- From the Fig. 15, there is no change in the throughput performance in case of CSMA/CA half-duplex, as it is not affected by the self-interference cancellation.
- On the other hand, PoCMAC achieves a higher throughput performance.
- When α is greater than 65 dB, the throughput performance levels off because the AP already uses its maximum transmit power and the self-interference is sufficiently suppressed.

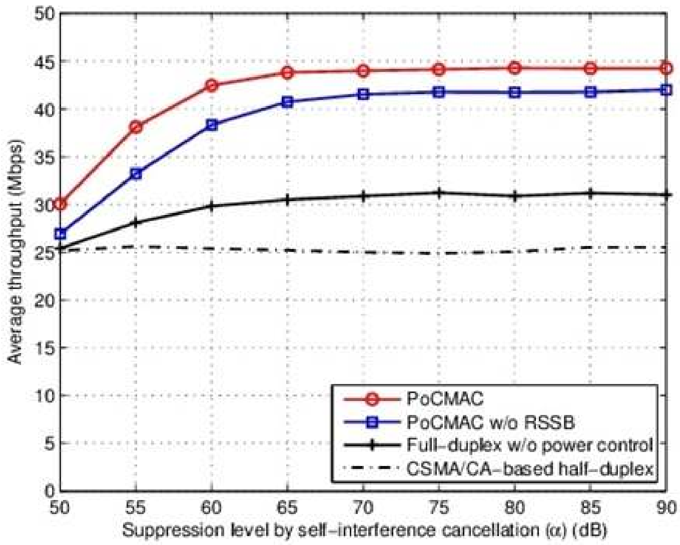


Fig-15. Average throughput with respect to the suppression level of self- interference cancellation when the number of clients is 10.

Conclusion:

In this study, the fundamental concept of in-band full-duplex wireless communication has been described. This tutorial has mainly two sections: 1st section includes basic study for the IBFD and medium access control design and 2nd section includes an example of this kind of MAC protocol. So, after studying the first section, the second section will provide a deeper knowledge on the MAC protocol for IBFD wireless communication.

References:

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