A Basic Analysis of Medium Access Control for Full-duplex WLAN

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***Abstract*—Current half duplex wireless communications are reaching the Shannon limit. Previous works have studied full-duplex (FD) wireless communications medium access control (MAC) schemes to double a communication capacity. However, general analysis and guideline for FD wireless communications MAC protocols design have not been shown. In this paper, the role of MAC in FD communication enabled wireless network are assessed by theoretical analysis. We show an optimal MAC design for wireless local area network (LAN) in which FD capable user terminals and only HD capable user terminals coexist. From our analysis, we show that a FD capable access point (AP) is enable to change approximately 90 % HD communications to FD communication, even when there are only HD capable user terminals.**

I. Introduction

Recently, there has been an explosive growth of mobile traffic demand. Mobile data traffic increased 65% between the first quarter of 2013 and the first quarter of 2014. If this rate continues, mobile data traffic will increase by 100 times in the next decade [1]. In addition, the number and types of nodes that connect to the Internet are also increasing, making it necessary to achieve a higher data rate within prevailing resource and bandwidth limitations.

Current wireless communications schemes assume half-duplex wireless communications in a single frequency. When one node receive data from another node, the node cannot transmit data in order to avoid collision. The current collision avoidance and half-duplex communications scheme are reaching the Shannon limit in channel capacity. Recent developments [2] in physical layer techniques of self-interference cancelation reached to 110dB, which enable nodes to transmit and receive on a same frequency at the same time. Self-interference cancelation schemes have potential to double the wireless communication capacity. However, to take advantage of full-duplex capable potentiality, new medium access control (MAC) design for full-duplex (FD) communication is necessary.

This paper focuses on MAC protocol for wireless local area network (LAN) that enables FD communication. There have been extensive studies of MAC protocol for FD wireless LAN in recent years [3]–[8]. [3] proposed MAC design for the wireless LAN with three nodes; one is FD capable AP and others are HD capable UTs. In [4], power-controlled MAC (PocMAC) to avoid and reduce inter-user interference was proposed. Full-duplex multi channel MAC (FD-MMAC) was proposed to mitigate hidden terminal problem in multi channel situation by using busy tones [5]. [6] proposed FD-MAC for wireless LAN which contains a full-duplex capable access point (AP) and half-duplex user terminals. RTS/FCTS is proposed in [8]. RTS/FCTS mechanism support both bi-directional and two directional FD communication. These previous [3]–[7] studies have shown that MAC designs are key to enhance the capacity in FD capable wireless LAN. However, previous studies have shown their own FD MAC potential and performances. In this paper, we show a fundamental theoretical analysis for FD MAC protocols. Results of our fundamental theoretical analysis are applicable to a number of FD MAC protocol design.

The rest of this paper is organized as follows: In Section II, we introduce FD capable wireless LAN and the two types of full-duplex communication; in Section III, we show the theoretical analysis of FD communication occurrence probability in FD wireless LAN as shown in Section II; we show an affect of inter-user interference and an efficacy of UTs selection for avoiding inter-user interference in Section IV; in Section V we show some discussions; and finally, the conclusion is drawn in Section VI.

II. System Model

We consider the wireless LAN that consists FD capable AP and multiple FD user terminals (UTs) and HD UTs. FD UTs are defined as FD capable user terminals; HD UTs are not able to do full-duplex communication. In this FD/HD user terminal coexisting wireless LAN, AP transmit and receive data to/from UTs. There is no wireless communication between UTs.

In this paper, we define the two types of FD communication in the FD capable wireless LAN. One is bi-directional FD communication, the other is two directional FD communication. In bi-directional FD communication, AP and a FD capable UT transmit and receive data to/from each other at the same time. Figure 1 shows an example of bi-directional FD communication. In fig. 1, FD capable UT (FD_1) transmit data to AP, and AP transmit data to FD_1 in a single carrier at the same time.

On the other hand, in two directional FD communication,

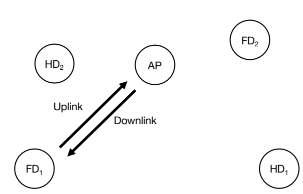

Fig. 1. An example of bi-directional FD communication

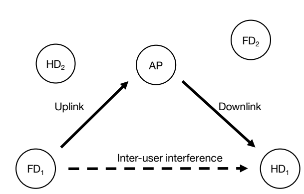

Fig. 2. An example of two directional FD communication

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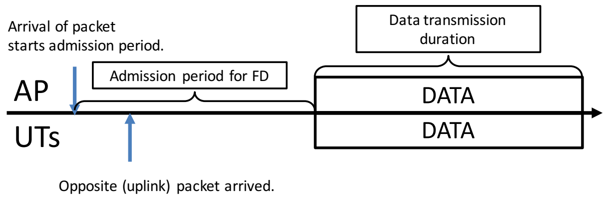

Fig. 3. The packet arrives of opposite direction, FD is performed

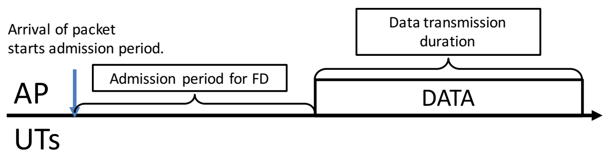

Fig. 4. The packet of opposite direction does not arrive in admission period, ending in HD

a UT transmit data to AP, and AP transmit data to another UT. In two directional FD communication, UTs are not necessary to have FD capability. Figure 2 shows an example of two directional FD communication, that FD capable UT (FD_1) transmit data to AP, and AP transmit data to HD_1 in a single carrier at the same time. In addition to the uplink/downlink transmission, inter-user interference occurs. Receiving UT receive signals from not only AP but also signals transmitting UT. Signals from transmitting UT becomes inter-user interference at receiving UT.

III. Full-duplex Gain

Some studies have shown that the handshake mechanism of FD MAC design help nodes to do FD communication [3]–[8]. If there is only downlink (or uplink) traffic, no MAC design can make FD transmission. When both of uplink and downlink packets arrives, FD transmission occurs. We simplify the mac protocol. We define an admission period; deterministic duration. Moreover, we define that each transmission is independent. When one uplink or downlink packet arrives, the packet will wait for an opposite packet arrival within the admission period. Figure 3 shows that a downlink packet occurs (a packet arrives at AP) and within admission period uplink (opposite) packet occurs (a packet arrives at UTs) then FD transmission occurs. In fig. 4, a downlink packet occurs, however, no uplink (opposite) packet comes. Thus, the situation pictured in fig. 4 end to a HD transmission. Traffic pattern is related to FD communication opportunity. In this section, we show the relation of packet arrival rate and FD communication opportunity without inter-user interference.

In this section, a gain of FD communication is calculated in the FD/HD coexisting wireless LAN. We calculate probabilities; occurrence probability of bi-directional FD, two directional FD, HD communication. Then, we calculate the gain of FD communication by using these probabilities.

Table I shows variables that are used in this paper. The variable m and n denote the number of full-duplex and half-duplex user terminals; $\mathrm{UT}_i\{i|1 \leq i \leq m\}$ presents full-duplex user terminal; $\mathrm{UT}_i\{i|m+1 \leq i \leq m+n\}$ presents half-duplex user terminal; $\lambda_{\mathrm{APUT}i}$ is the average packet to UT_i arrival rate at AP (packets/sec.); $\lambda_{\mathrm{UT}i}$ is the average packet arrival rate at UT_i (packets/sec.); T_a,T_t are defined as Length of full-duplex admission duration and of transmission duration (sec.); P_{BFD}, P_{TFD} and P_{HD} are occurrence probabilities of bi-directional FD, two directional FD and HD communication; G_{FD} is gain of FD communication (%).

TABLE I. Variables

Variables, Functions	Explanation
m	Number of Full-duplex user terminals
n	Number of Half-duplex user terminals
$\mathrm{UT}_i\{i\|1 \leq i \leq m\}$	Full-Duplex user terminal(i)
$\mathrm{UT}_i\{i\|m+1 \leq i \leq m+n\}$	Half-Duplex user terminal(i)
$\lambda_{\mathrm{APUT}i}$	The average packet to UT_i arrival rate at AP (packets/sec.)
$\lambda_{\mathrm{UT}i}$	The average packet arrival rate at UT_i (packets/sec.)
T_a	Length of full-duplex admission duration (sec.)
T_t	Length of transmission duration (sec.)
P_{BFD}	Occurrence probability of bi-directional FD communication
P_{TFD}	Occurrence probability of two directional FD communication
P_{HD}	Occurrence probability of HD communication
G_{FD}	Gain of FD capability (%)

First, we show the occurrence probability of bi-directional FD communication (P_{BFD}). Packet arrivals is Poisson arrivals. Conditional probability that a downlink packet for UT_j arrives when one uplink or downlink packet arrives in this wireless LAN, is $\lambda_{\mathrm{APUT}j}/(\sum_{i=1}^{m+n}\lambda_{\mathrm{UT}i}+\sum_{i=1}^{m+n}\lambda_{\mathrm{APUT}i})$. Probability of opposite (uplink) packets arrival in admission period is $\left\{1-\exp\left(-\sum_{i=1}^{m+n}\lambda_{\mathrm{UT}i}T_a\right)\right\}$. Conditional probability that an uplink packet for UT_j arrives first when opposite (uplink) packets arrives in admission period is $\lambda_{\mathrm{UT}j}/\sum_{i=1}^{m+n}\lambda_{\mathrm{UT}i}$. On the other hand, we see that an uplink packet for UT_j arrives first case. Conditional probability that an uplink packet for UT_j arrives when one uplink or downlink packet arrives in this system, is $\lambda_{\mathrm{UT}j}/\sum_{i=1}^{m+n}\lambda_{\mathrm{UT}i}+\sum_{i=1}^{m+n}\lambda_{\mathrm{APUT}i}$. Probability of opposite (downlink) packets arrival in admission period is $\left\{1-\exp\left(-\sum_{i=1}^{m+n}\lambda_{\mathrm{APUT}i}T_a\right)\right\}$. Conditional probability that an uplink packet for UT_j arrives first when opposite (downlink) packets arrives in admission period is $\lambda_{\mathrm{APUT}j}/\sum_{i=1}^{m+n}\lambda_{\mathrm{APUT}i}$. Therefore, the occurrence probability of bi-directional FD communication (P_{BFD}) is given by

$$
\begin{aligned}
P_{\mathrm{BFD}} = \sum_{j=1}^{m} \Bigg[& \frac{\lambda_{\mathrm{APUT}j}}{\sum_{i=1}^{m+n}\lambda_{\mathrm{UT}i}+\sum_{i=1}^{m+n}\lambda_{\mathrm{APUT}i}} \\
& \times \left\{1-\exp\left(-\sum_{i=1}^{m+n}\lambda_{\mathrm{UT}i}T_a\right)\right\} \times \frac{\lambda_{\mathrm{UT}j}}{\sum_{i=1}^{m+n}\lambda_{\mathrm{UT}i}} \Bigg] \\
+ \sum_{j=1}^{m} \Bigg[& \frac{\lambda_{\mathrm{UT}j}}{\sum_{i=1}^{m+n}\lambda_{\mathrm{UT}i}+\sum_{i=1}^{m+n}\lambda_{\mathrm{APUT}i}} \\
& \times \left\{1-\exp\left(-\sum_{i=1}^{m+n}\lambda_{\mathrm{APUT}i}T_a\right)\right\} \times \frac{\lambda_{\mathrm{APUT}j}}{\sum_{i=1}^{m+n}\lambda_{\mathrm{APUT}i}} \Bigg] \quad (1)
\end{aligned}
$$

In the same way as the bi-directional FD (P_{BFD}), P_{TFD} is calculated as,

$$P_{\mathrm{TFD}} = \sum_{j=1}^{m+n} \Bigg[\frac{\lambda_{\mathrm{APUT}j}}{\sum_{i}^{m+n} \lambda_{\mathrm{UT}i} + \sum_{i=1}^{m+n} \lambda_{\mathrm{APUT}i}} \times \left\{ 1 - \exp\left(- \sum_{i=1}^{m+n} \lambda_{\mathrm{UT}i} T_a \right) \right\} \times \frac{\sum_{i=1, i\neq j}^{m+n} \lambda_{\mathrm{UT}i}}{\sum_{i=1}^{m+n} \lambda_{\mathrm{UT}i}} \Bigg] + \sum_{j=1}^{m+n} \Bigg[\frac{\lambda_{\mathrm{UT}j}}{\sum_{i=1}^{m+n} \lambda_{\mathrm{UT}i} + \sum_{i=1}^{m+n} \lambda_{\mathrm{APUT}i}} \times \left\{ 1 - \exp\left(- \sum_{i=1}^{m+n} \lambda_{\mathrm{APUT}i} T_a \right) \right\} \times \frac{\sum_{i=1, i\neq j}^{m+n} \lambda_{\mathrm{APUT}i}}{\sum_{i=1}^{m+n} \lambda_{\mathrm{APUT}i}} \Bigg] \quad (2)$$

The rest of transmission type is HD communications; P_{HD} is

$$P_{\mathrm{HD}} = \sum_{j=1}^{m} \Bigg[\frac{\lambda_{\mathrm{APUT}j}}{\sum_{i=1}^{m+n} \lambda_{\mathrm{UT}i} + \sum_{i=1}^{m+n} \lambda_{\mathrm{APUT}i}} \times \exp\left(- \sum_{i=1}^{m+n} \lambda_{\mathrm{UT}i} T_a \right) \Bigg] + \sum_{j=1}^{m} \Bigg[\frac{\lambda_{\mathrm{UT}j}}{\sum_{i=1}^{m+n} \lambda_{\mathrm{UT}i} + \sum_{i=1}^{m+n} \lambda_{\mathrm{APUT}i}} \times \exp\left(- \sum_{i=1}^{m+n} \lambda_{\mathrm{APUT}i} T_a \right) \Bigg] + \sum_{j=m+1}^{m+n} \Bigg[\frac{\lambda_{\mathrm{APUT}j}}{\sum_{i=1}^{m+n} \lambda_{\mathrm{UT}i} + \sum_{i=1}^{m+n} \lambda_{\mathrm{APUT}i}} \times \exp\left(- \sum_{i=1, i\neq j}^{m+n} \lambda_{\mathrm{UT}i} T_a \right) \Bigg] + \sum_{j=m+1}^{m+n} \Bigg[\frac{\lambda_{\mathrm{UT}j}}{\sum_{i=1}^{m+n} \lambda_{\mathrm{UT}i} + \sum_{i=1}^{m+n} \lambda_{\mathrm{APUT}i}} \times \exp\left(- \sum_{i=1, i\neq j}^{m+n} \lambda_{\mathrm{APUT}i} T_a \right) \Bigg]. \quad (3)$$

A. FD Occurrence for FD/HD User Terminals Percentage

First, we evaluate the FD occurrence with increasing FD user terminals (UTs) percentage ($\frac{m}{m+n} \times 100\%$) in the network to show the basic performance of FD/HD coexisting wireless LAN. Figure 5 shows the occurrence probability when the percentage of FD user terminals changes from 0 % to 100 %. To obtain the occurrence probability, we set values; Length of transmission duration T_t is defined as τ (sec.); Length of full-duplex admission period duration T_a is 0.5τ (sec.); we set same packet arrival rates for all the packet arrival type, $\lambda_{\mathrm{APUT}i} = \lambda_{\mathrm{UT}i} = 0.5/\tau$ (packets/sec.). These setting regarded as that T_a, $\lambda_{\mathrm{APUT}i}$, $\lambda_{\mathrm{UT}i}$ are normalized by T_t (τ).

Figure 5 shows the probability of bi-directional FD occurrence. The horizontal axis is percentage of FD user terminals in wireless LAN [%], and vertical axis is the probability of occurrence. As the percentage of FD user terminals in

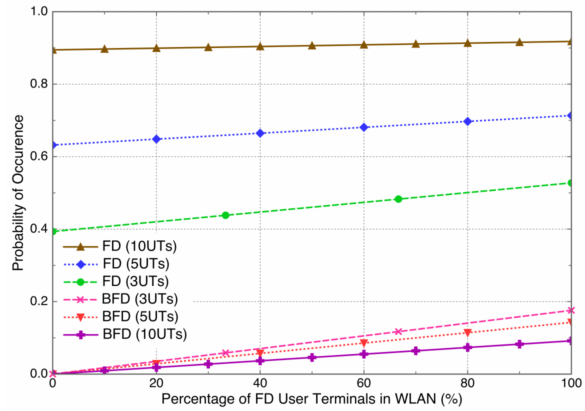

Fig. 5. Percentage of FD User Terminals in WLAN vs. Occurrence Probability

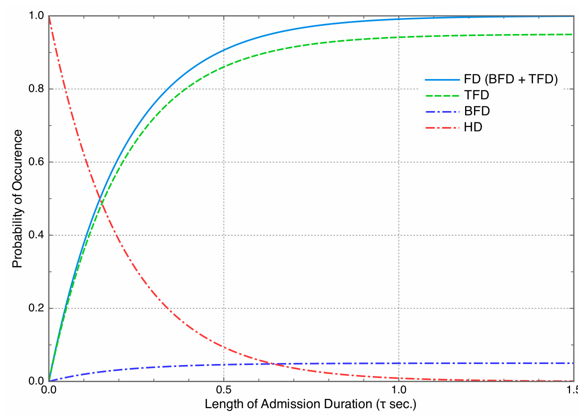

Fig. 6. Admission Duration vs. FD Occurrence Probability (FD5, HD5)

wireless LAN is grown, more FD communication occurs. When the number of user terminals in wireless LAN is 3, FD capability of user terminals raises 30 % of the FD occurrence probability. FD capability of user terminals have performance of increasing capacity, when the number of user terminals is low. However, when the number of user terminals is increased, the percentage of FD UTs becomes non-dominant. Importance of user terminals' FD capability depends on scale of wireless LAN.

B. FD Occurrence for Length of Admission Duration

Longer admission duration is expected to cause more FD communications. In this section, we show the relationship between FD occurrence and length of admission duration. Figure 6 shows the probability of bi-directional FD occurrence with variable admission duration length. To obtain the occurrence probability, we set values; Number of FD capable UTs (m) is 5; Number of HD capable UTs (n) is 5; Length of transmission duration T_t is defined as τ (sec.); We set same packet arrival rates for all the packet arrival type, $\lambda_{\mathrm{APUT}i} = \lambda_{\mathrm{UT}i} = 0.5/\tau$ (packets/sec.). These setting regarded as that $\lambda_{\mathrm{APUT}i}$, $\lambda_{\mathrm{UT}i}$ are normalized by T_t (τ).

The horizontal axis is length of admission duration, and vertical axis is the probability of occurrence. As the length of

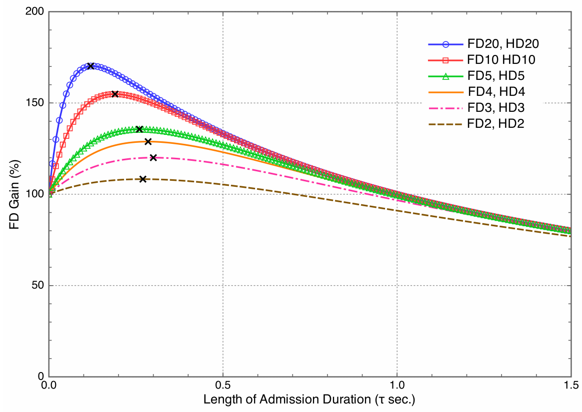

Fig. 7. Admission Duration vs. Gain of FD Capability

admission duration (T_a) is grown, more FD communication occurs. Figure 6 shows that approximately 90 % of communication becomes FD when the length of admission duration is 0.5. When evaluated only from the point of view of increasing the FD occurrence, the longer admission duration is better.

C. Optimum Admission Duration

In section III-A and III-B, the occurrence probability of FD communication is reported. In this section, we evaluate the FD communication gain. The longer admission period duration causes higher occurrence probability of FD communication. However, the longer admission period duration will become larger overhead for transmission. Therefore, there is tradeoff between higher occurrence probability of FD communication and larger overhead. We set the gain of FD capability as

$$G_{FD} = \frac{T_t}{T_a + T_t}(\alpha P_{\text{BFD}} + \beta P_{\text{TFD}} + P_{\text{HD}}), \tag{4}$$

when bi-directional FD communication obtains α times capacity of HD and two directional FD communication gains β times capacity of HD. We evaluate the gain of FD capability of different number user terminals situations. Figure 7 shows the relationship between the gain of FD capability and length of admission period duration. In fig. 7, length of transmission duration T_t is defined as τ (sec.); packet arrival rates are $\lambda_{\text{APUT}i} = \lambda_{\text{UT}i} = 0.5/\tau$ (packets/sec.); Capacity gains of FD α and β are 2, we assume that FD reaches double capacity of HD; Legend FDm, HDn means that the FD capable wireless LAN consists of FD capable AP, m FD capable user terminals and n HD capable user terminals.

Figure 7 shows the optimum admission period duration depend on the number of user terminals. Adaptive admission period duration is necessary for the optimum MAC design. FD gain becomes less than 100 % when the admission period duration is larger than transmission time duration (1.0τ), because FD capability enhance capacity only twice. Thus, FD MAC admission duration should be adaptive and less than transmission time duration.

IV. Efficacy of User Selection for Avoiding Inter-user Interference

In section III, we evaluate the performance of FD MAC design without inter-user interference situation. These results, in sec. III, shows optimal case and possibility of FD wireless LAN. However, in practical, there is inter-user interference problem in FD wireless LAN [3], [4]. Inter-user interference becomes a cause of decrease capacity of wireless LAN.

A. Affect of Inter-user Interference

First, we show an affect of inter-user interference. Table II shows variables that are used for evaluating an affect of inter-user interference. n_{ij} denotes the inter-user interference index. n_{ij} becomes $n_{ij} = 0$ when UT_i cause inter-user interference to UT_j; p_{IUI} presents probability of inter-user interference occurs; $P_{\text{BFDw/IUI}}$, $P_{\text{TFDw/IUI}}$ and $P_{\text{HDw/IUI}}$ are occurrence probabilities of bi-directional FD, two directional FD and HD communication in inter-user interference existing situation; $P_{\text{BFDw/US}}$, $P_{\text{TFDw/US}}$ and $P_{\text{HDw/US}}$ are occurrence probabilities of bi-directional FD, two directional FD and HD communication with user selection (US) capable MAC protocol. More detail about user selection is mentioned in Sec. IV-B

TABLE II. Variables for the Inter-user Interference Situation

Variables, Functions	Explanation
n_{ij}	Inter-user interference index ($n_{ij} = 0$ when UT_i cause inter-user interference to UT_j)
$p_{IUI}(= \frac{1}{(m+n)^2}\sum_{i=1}^{m+n}\sum_{j=1}^{m+n} n_{ij})$	Probability of inter-user interference occurs
$P_{\text{BFDw/IUI}}$	Occurrence probability of bi-directional FD communication with inter-user interference
$P_{\text{TFDw/IUI}}$	Occurrence probability of two directional FD communication with inter-user interference
$P_{\text{HDw/IUI}}$	Occurrence probability of HD communication with inter-user interference
$P_{\text{BFDw/US}}$	Occurrence probability of bi-directional FD communication with user selection
$P_{\text{TFDw/US}}$	Occurrence probability of two directional FD communication with user selection
$P_{\text{HDw/US}}$	Occurrence probability of HD communication with user selection

Inter-user interference is innocuous for bi-directional FD communication. Occurrence probability of bi-directional FD communication with inter-user interference can be calculated as

$$P_{\text{BFDw/IUI}} = P_{\text{BFD}}. \tag{5}$$

Some cases of two-directional FD communication cannot be supported in the situation with inter-user interference. Some two-directional FD communication cases becomes HD communication. Thus, $P_{\text{TFDw/IUI}}$ and $P_{\text{HDw/IUI}}$ are given by

$$P_{\text{TFDw/IUI}} = (1 - p_{IUI})P_{\text{TFD}} \tag{6}$$

$$P_{\text{HDw/IUI}} = p_{IUI}P_{\text{TFD}} + P_{\text{HD}}. \tag{7}$$

B. Effect of Ideal User Selection for Avoiding Inter-user Interference

The affect of inter-user interference is shown in Eq. 5-7. Some studies mitigate the inter-user interference [3], [4]. PoCMAC proposed select user terminals to avoid inter-user interference by using receiving power [4]. We show an effect of ideal user selection schemes in inter-user interference situation. MAC without user selection accept two-directional FD communication which causes inter-user interference.

First, we calculate occurrence probability of bi-directional FD communication with user selection ($P_{\mathrm{BFDw/US}}$). When first uplink (or downlink) packet arrives, ideal user selection scheme waits acceptable opposite (downlink/uplink) packet; Acceptable means that nodes can transmit data without inter-user interference. Conditional probability that a downlink packet for UT_j arrives when one uplink or downlink packet arrives in this wireless LAN, is $\lambda_{\mathrm{APUT}j}/(\sum_{i=1}^{m+n}\lambda_{\mathrm{UT}i} + \sum_{i=1}^{m+n}\lambda_{\mathrm{APUT}i})$. Probability of opposite (uplink) packets (except for UTs causing inter-user interference for UT_j) arrival in admission period is $\left\{1-\exp\left(-\sum_{i=1}^{m+n} n_{ij}\lambda_{\mathrm{UT}i}T_a\right)\right\}$. Conditional probability that an uplink packet for UT_j arrives first when opposite (uplink) packets arrives in admission period is $\lambda_{\mathrm{UT}j}/\sum_{i=1}^{m+n} n_{ij}\lambda_{\mathrm{UT}i}$. An uplink packet for UT_j arrives first case is also calculated in the same way as the downlink packet first case. Therefore, the occurrence probability of bi-directional FD communication with user selection is given by

$$
\begin{aligned}
P_{\mathrm{BFDw/US}} = &\sum_{j=1}^{m}\Bigg[\frac{\lambda_{\mathrm{APUT}j}}{\sum_{i=1}^{m+n}\lambda_{\mathrm{UT}i}+\sum_{i=1}^{m+n}\lambda_{\mathrm{APUT}i}} \\
&\times\left\{1-\exp\left(-\sum_{i=1}^{m+n} n_{ij}\lambda_{\mathrm{UT}i}T_a\right)\right\} \\
&\times\frac{\lambda_{\mathrm{UT}j}}{\sum_{i=1}^{m+n} n_{ij}\lambda_{\mathrm{UT}i}}\Bigg] \\
&+\sum_{j=1}^{m}\Bigg[\frac{\lambda_{\mathrm{UT}j}}{\sum_{i=1}^{m+n}\lambda_{\mathrm{UT}i}+\sum_{i=1}^{m+n}\lambda_{\mathrm{APUT}i}} \\
&\times\left\{1-\exp\left(-\sum_{i=1}^{m+n} n_{ji}\lambda_{\mathrm{APUT}i}T_a\right)\right\} \\
&\times\frac{\lambda_{\mathrm{APUT}j}}{\sum_{i=1}^{m+n} n_{ji}\lambda_{\mathrm{APUT}i}}\Bigg]. \qquad (8)
\end{aligned}
$$

In the same way as the bi-directional FD, $P_{\mathrm{TFDw/US}}$ is given by

$$
\begin{aligned}
P_{\mathrm{TFDw/US}} = &\sum_{j=1}^{m+n}\Bigg[\frac{\lambda_{\mathrm{APUT}j}}{\sum_{i=1}^{m+n}\lambda_{\mathrm{UT}i}+\sum_{i=1}^{m+n}\lambda_{\mathrm{APUT}i}} \\
&\times\left\{1-\exp\left(-\sum_{i=1}^{m+n} n_{ij}\lambda_{\mathrm{UT}i}T_a\right)\right\} \\
&\times\frac{\sum_{i=1,i\neq j}^{m+n}\lambda_{\mathrm{UT}i}}{\sum_{i=1}^{m+n} n_{ij}\lambda_{\mathrm{UT}i}}\Bigg] \\
&+\sum_{j=1}^{m+n}\Bigg[\frac{\lambda_{\mathrm{UT}j}}{\sum_{i=1}^{m+n}\lambda_{\mathrm{UT}i}+\sum_{i=1}^{m+n}\lambda_{\mathrm{APUT}i}} \\
&\times\left\{1-\exp\left(-\sum_{i=1}^{m+n} n_{ji}\lambda_{\mathrm{APUT}i}T_a\right)\right\} \\
&\times\frac{\sum_{i=1,i\neq j}^{m+n}\lambda_{\mathrm{APUT}i}}{\sum_{i=1}^{m+n} n_{ji}\lambda_{\mathrm{APUT}i}}\Bigg]. \qquad (9)
\end{aligned}
$$

The rest is HD communication; $P_{\mathrm{HDw/US}}$ is given by

$$P_{\mathrm{HDw/US}} = 1-(P_{\mathrm{BFDw/US}}+P_{\mathrm{TFDw/US}}). \qquad (10)$$

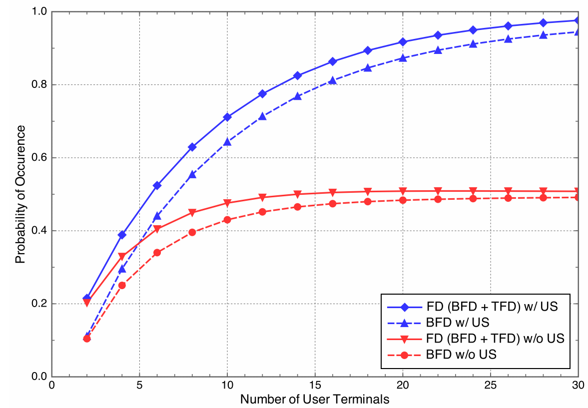

Fig. 8. Number of User Terminals vs. FD Occurrence Probability

C. FD Occurrence for Variable Number of User Terminals

We evaluate FD occurrence probability for variable number of user terminals in order to compare MAC with user selection scheme and without user selection scheme. It is expected that user selection scheme increase the occurrence probability of FD communication. Therefore, in order to evaluate user selection performance, we evaluated the relation between number of user terminals and occurrence probability of FD communication. In fig. 8, length of transmission duration T_t is defined as τ (sec.); Length of full-duplex admission period duration T_a is 0.5τ (sec.); probability of inter-user interference occurrence (p_{IUI}) is 0.5; we set same packet arrival rates for all the packet arrival type, $\lambda_{\mathrm{APUT}i} = \lambda_{\mathrm{UT}i} = 0.5/\tau$ (packets/sec.); Number of FD capable user terminals and HD capable user terminals are same.

Figure 8 shows that occurrence probability of FD communication of MAC w/ user selection (FD w/ US) and MAC w/o user selection (FD w/o US). When the number of user terminals is large, user-selection scheme enhances FD communication. However, when the number of user terminals is small, user-selection have small impact. These results are theretically shown as

$$\lim_{n+m\to\infty}\frac{P_{\mathrm{FDw/IUI}}}{P_{\mathrm{FDw/US}}} \simeq (1-p_{IUI}) \qquad (11)$$

$$\lim_{n+m\to 0}\frac{P_{\mathrm{FDw/IUI}}}{P_{\mathrm{FDw/US}}} \simeq 1. \qquad (12)$$

D. FD Occurrence for Variable Inter-user Interference Occurrence

In section IV-C, we show the probability of FD occurrence when the probability of inter-user interference occurrence (p_{IUI}) is 0.5. However, the probability of inter-user interference occurrence (p_{IUI}) is depend on a topology of wireless LAN. In this section, we show the probability of FD occurrence for variable probability of inter-user interference occurrence(p_{IUI}). In fig. 9, length of transmission duration T_t is defined as τ (sec.); Length of full-duplex admission period duration T_a is 0.5τ (sec.); we set same packet arrival rates for all the packet arrival type, $\lambda_{\mathrm{APUT}i} = \lambda_{\mathrm{UT}i} = 0.5/\tau$ (packets/sec.); Number of FD capable user terminals is 5; and

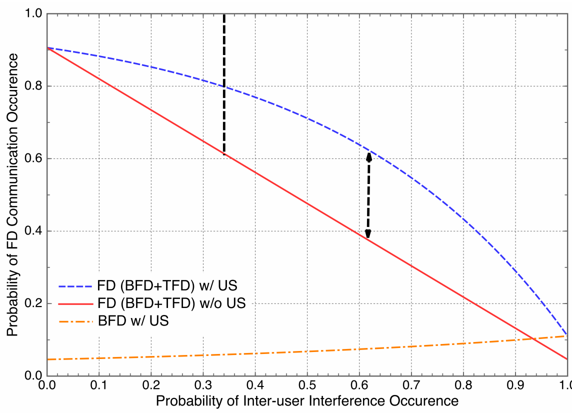

Fig. 9. Inter-user Interference Occurrence vs. FD Occurrence (FD5, HD5)

HD capable user terminals is 5. Figure 9 shows the relationship between the probability of FD occurrence and variable probability of inter-user interference occurrence(p_{IUI}).

Figure 9 shows that higher inter-user interference decreases the FD occurrence. Gain of user selection scheme raises as the probability of inter-user interference occurrence raises. When the probability of inter-user interference occurrence (p_{IUI}) is 1, gain of user selection scheme becomes 2. In this case, all the FD communication become bi-directional FD communication. In addition to that, we see the difference of the probability of FD communication occurrence. Difference of FD occurrence probability between w/ and w/o user selection is 20 % when the probability of inter-user interference occurrence (p_{IUI}) is 0.6. User selection scheme change approximately 40 % of HD communication to FD communication when the probability of inter-user interference occurrence(p_{IUI}) is 0.34. Thus, user-selection scheme enhances the wireless LAN capacity by improving the probability of FD occurrence.

V. Discussion

A. Correlation between Uplink and Downlink Traffic

In Section III and IV, we assume that uplink and downlink packet arrivals are independent. However, in practical, there is a correlation between uplink and downlink packet arrival rate for one user. For example, when a user uses voice over internet protocol (VoIP) service, uplink and downlink of user traffic occurs at the same time. If there is the correlation of uplink and downlink traffic for one user, bi-directional full-duplex transmission occurs more frequently than our evaluation. Necessary of full-duplex capability for user terminals will depend on user application.

B. Packet Loss

In section II, we assume an arrived packet wait deterministic time duration (t_a), then packet can be transmitted. When many packets arrive at wireless LAN system, packet losses will be caused. We do not consider about throughput but about occurrence probabilities of bi-directional, two directional FD and HD. Thus, packet losses are negligible. There are possibilities that more communication becomes full-duplex communication.

C. Inter-user Interference Cancelation

We assume, in Section IV, inter-user interference avoidance. Some interference cancellation schemes are possible to be used as inter-user interference cancelation techniques. In recent years, several interference cancelation technique is studied [9], [10] . Successive interference cancelation (SIC) is proposed in [9] . SIC can split collided signals by using difference of receiving signals power. In addition to that, [10] proposed FD multi user multiple-input multiple-output (MU-MIMO) systems. MU-MIMO technique enables nodes to communicate with multiple other nodes. These techniques enable node to receive signals from several transmitters at the same. Inter-user interference cancelation causes more full-duplex communications.

VI. Conclusion

In this paper, we show theretical analysis of MAC for FD capable wireless LAN. Performance evaluation shows that a FD capable access point (AP) and avoiding inter-user interference is key to enhance the next generation wireless network capacity. Our ongoing and future research will discuss inter-user interference in more detail.

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