Experimental Evaluation of Interference Robustness for Frequency Spectrum Sharing in WLAN Systems

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***Abstract*—Wireless local area networks (WLAN) are widely spread over office and home for supporting various applications. From the explosive growth of WLAN, a lot of wireless terminals share frequency resource and thus the drop of throughput and the degradation of communication quality are serious problem. In WLAN, a function of collision avoidance and a capture effect avoid the significant drop of communication quality. However, the product of WLAN has a freedom for the construction of receiver architecture. As a result, the sensitivity of capture effect and the performance of demodulation may be different for each product. In this paper, the experimental evaluation for clarifying the performance of receiver with each product of WLAN is conducted. In this experiment, the resource sharing between the artificial interference source and some products of WLAN is performed.**

I. Introduction

A wireless local area network (WLAN) has been being extended, significantly and thus the throughput of WLAN is nearly over that of wired LAN (Ethernet). The recent standards of WLAN are IEEE802.11n [1] and IEEE802.11ac [2] and their frequency bands are 2.4 GHz and 5 GHz. The systems of WLANs are widely spread over the public places, such as station and airport, the home, and the office. As a result, access points and WLAN terminal (stations) of WLAN are explosively increased. Since the frequency spectrum which are the wireless communication resources are strictly limited, the depletion of it is more serious problem [3]. The sharing of frequency spectrum among various wireless communication systems is more important problem.

The wireless access scheme of WLAN for the frequency spectrum sharing is defined in a media access control (MAC) and it is a carrier sense multiple access with collision avoidance (CSMA/CA). The CSMA/CA can avoid the packet collision caused by the simultaneous access from the other systems owing to a carrier sensing. The sensitivity of carrier sensing, however, is not stable because the multi-path fading causes the fluctuation of detected spectrum power or energy. If the carrier sensing fails to detect the wireless access from the other system, the packet collision occurs. This failure is referred to as the hidden node terminal problem [4]. Even in the occurrence of packet collision, if the signal power of a packet is so small that the effect of it is negligible, it is possible to decode the packet. This event is referred to as capture effect [5]. The frequency usage efficiency in spectrum sharing among systems will be improved when the capture effect is used, actively.

WLAN is one of the distributed systems. When two distributed WLAN systems shares the common frequency bandwidth, there are three conditions, time division, spatial division, and hidden terminal problem. In the condition of time division, a WLAN system can detect the packet access from the other system with high accuracy and thus two WLAN systems uses the common frequency spectrum, alternately. In the condition of spatial division, two WLAN systems access the frequency spectrum without mutual interference between them. In the condition of hidden terminal, the simultaneous access between two WLAN systems occurs because these fail to detect the wireless access and thus the packet loss occur. The distributed WLAN systems should avoid sharing the common frequency spectrum under the condition of hidden terminal. In [6], each condition depends on the distance between two systems. In the short, the middle, and the long distance between two systems, the conditions are time division, hidden terminal condition, and spatial division, respectively. These distances depends on the architecture of wireless equipment in WLAN. Recently, various kinds of wireless architecture in WLAN are produced. The very small architecture of WLAN for the internet of things is produced and it has the small low gain antenna. The architecture with high specification is also produced for broad band access and it has the smart antenna for obtaining high gain and complicate signal process for high sensitivity receiver. In many cases, the specification of architecture is not published and has freedom for product maker. Therefore, the capability of each WLAN, such as capture effect, the accuracy of carrier sensing, should be evaluated in order to clarify the conditions of spectrum sharing. As a result, the suitable condition for spectrum sharing can be clarified.

This paper evaluate the capture effect and the sensitive of carrier sensing for the commercial production of WLAN system in the field experiment. We have three commercial WLAN productions. These three products are the WLANs with two diversity antenna, that with three aray antenna, and buit-in antenna, respectively. We construct the artificial interference whose configuration in base band packet is the

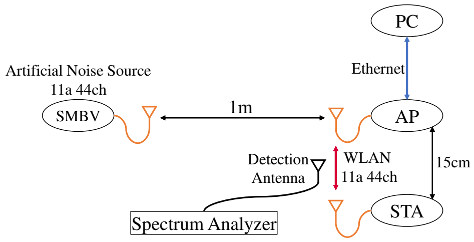


Fig. 1: System Model

TABLE I: Parameters of the WLAN System

Access Point	Product A, B, and C
WLAN Adapter	ELECOM Corp., WDC-433DU2H
WLAN Standard	IEEE 802.11a
Center Frequency	5.22GHz (W52 44ch)
Maximum Transmission Unit	1500 bytes
Transport Protocol	UDP

same as WLAN standard, but the wireless access protocol is not. There are two access rules, the continuous sending of packets with short stop period and that with long stop period. The first access rule is suitable for evaluating the capture effect because the stop period is very small and the signal of the WLAN system and the artificial interference surely collide.The success of demodulation can be decided by the existence of acknowledgement packet. On the other hand, in the artificial interference with long stop, the period of access stop is longer than the time duration of access packet. If the commercial production of WLAN systems can detect the artificial interference by carrier sensing, the commercial WLAN system can access to the channel during the stop period of artificial interference. This is the condition of time division. Therefore, the accuracy of carrier sensing with the commercial products of WLAN can be evaluated from the condition of time division or not. From the experimental evaluation, the differences of the capture effect and carrier sensing among the three commercial WLAN products are clarified.

II. Overview of System Configuration and Measurement Environment

A. System Configuration

Figure 1 shows an overview of measurement system. In this figure, the SMBV, the AP, and the STA are the signal generator for artificial interference, the access point, and the station of WLAN, respectively. Table I shows the parameters of WLAN system. While the AP or the STA keeps sending the data to the other terminal, the SMBV emits the artificial noise with using the same channel. Therefore, the AP and the STA suffer from the interference from SMBV. The antenna for detecting the signal of data packet is near both AP and STA because it can detects so high signal power that the false alarm and the misdetection can be avoided [6]. The data traffic passed through the wireless channel between AP and STA are generated by iperf3 [7]. Table II shows the

TABLE II: Setting of iperf3

Protocol	UDP
Measurement Time	10000sec
Port	5201
Bandwidth	300Mbps
Buffer Length	32Kbytes

TABLE III: Basic Specifications of Each AP and STA

	Product A	Product B	Product C	STA
Release Date	March, 2006	July, 2007	August, 2016	March, 2014
WLAN Standard	IEEE 802.11a	IEEE 802.11a	IEEE 802.11a	IEEE 802.11a
Antenna	External 2 Antennas (Diversity Antenna)	External 3 Antennas	Incorporated 2 Antennas	1 Antenna
Transmission System	OFDM	OFDM	OFDM	OFDM

system configuration of iperf3. As soon as the signal detection with spectrum analyzer is finished, the iperf3 is immediately stopped.

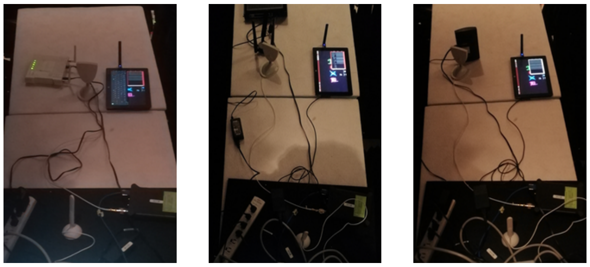
The communication links from PC to STA and from STA to PC are referred to as download and upload, respectively. One of the three commercial WLAN products A, B, and C are used for the access point. The antennas of the products A, B, and C are the diversity antenna with two arrays, the directional antenna with three arrays, and the built-in antenna, respectively. The transmit power of three products cannot be common. In this measurement, we set the minimum level of transmit power in each product. Table III and Fig. 2 show the configuration and the overview of the measurement environment in each product, respectively.

B. Artificial Interference

Table IV shows the parameters of artificial interference. The generated artificial interference does not have the function of wireless access control for avoiding the packet collision. Instead, it is periodically generated. Figure 3 shows the emitted pattern of artificial interference. No acknowledge signal (ACK signal) is generated for these artificial interference signals.There are two patterns. In first pattern and second one, the stop periods in frame by frame are short and long, respectively. In the pattern with short period, when the WLAN system detects the short stop period, it emits the packet. The artificial interference, however, is also emitted after the short stop. Therefore, the packet collision between the WLAN system and the generator of artificial interference occurs, certainly.

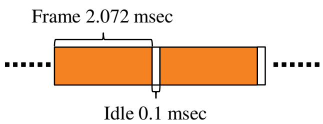
The purpose of using the artificial interference with short stop time is the evaluation of capture effect. If the packet access of WLAN system is still successful, the artificial interference is negligible for WLAN system and thus the capture effect is active.

In the second pattern of the artificial interference, the stop period is much larger than the length of the packet composed by the modulation and coding scheme (MCS) for minimum throughput. If the WLAN system can detect the vacant of channel, it can send the data packet to the receiver without

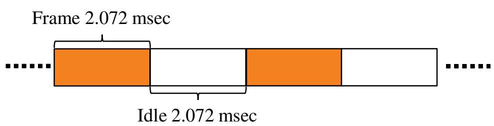


(a) Product A (b) Product B (c) Product C

Fig. 2: Measurement Environment



(a) Signal 1



(b) Signal 2

Fig. 3: Pattern of Artificial Interference Signals

the effect of the artificial interference. If the carrier sensing fails to detect the vacant of channel, which is false alarm, the WLAN system has the fewer opportunities to access channel. As a result, the throughput is reduced. Therefore, the purpose of using the second pattern of artificial noise is the evaluation of sensitivity of carrier sensing in each product.

C. Signal Detection by Spectrum Analyzer

Table V shows the parameters of the spectrum analyzer with real time function. In Ref. [6], two spectrum analyzer detect the signal power in the two remote WLAN systems, simultaneously. These require the control signal for timing synchronization. Owing to the simultaneous signal detection in two remote WLAN systems, the wireless access protocols of two systems under the mutual interference can be analyzed. In this evaluation, the artificial interference is emitted in a regular manner. Therefore, the protocol analysis is not necessary. In this evaluation, one spectrum analyzer is used for analysis the access protocol of WLAN system.

The detection antenna of spectrum analyzer is located near AP and STA for securing the larger signal power than that of artificial interference. As a result, the impact of artificial interference for analyzing the protocol of WLAN systems can be avoided.

TABLE IV: Parameters of the Interference Source

Signal Generator	Rohde & Schwarz Inc., SMBV100A
Antenna	Corega Inc., CG-WLANT01I
WLAN Standard	IEEE 802.11a
Center Frequency	5.22GHz
Modulation Method	BPSK
Code Rate	1/2
PHY Rate	6Mbps
Data Length	1500bytes (PRBS-9)
Transmission Time	2.072ms
Idle Time	0.1ms and 2.072ms

TABLE V: Parameters of the Spectrum Analyzer

Real-Time Spectrum Analyzer	Tektronix Inc., RSA306B
Detection Antenna	Corega Inc., WF1974
Center Frequency	5.22GHz
Acquisition Bandwidth	2.5MHz
Sampling Rate	3.5MSamples/sec
Number of Samples	1MSamples

III. Measurement Results

A. Packet Analyze from Detected Signal Power

Figure 5 shows the time versus the detected signal power passed through low pass filter. For packet analyze, the two level decision with threshold is performed to the detected signal power. Since the detection antenna is as near as to AP and STA, the detected signal power is so large that the false alarm and the miss detection does not occur. After two level decision, the idle time and the active time are specified. As a result, the time length of an inter frame space (IFS), back off time, and data and ACK frames can be measured. WLAN has the rate adaptation with controlling modulation and coding scheme (MCS). Table VI shows the relationship among physical level data rate (PHY Rate), secondary modulation, primary modulation, code rate , and data frame length. The data frame length can be calculated by the frame format given by Fig. 4, PHY Rate, and minimum Ethernet frame (1500 byte) [8]. From this table VI, each MCS level has the peculiar data frame length. Therefore, we can recognize the physical level throughput in accordance with the measured data frame length.

B. Performance Analysis

Four indicators that average PHY rate, TP_{UDP}, R, and N_{ALL} can be obtained from measurement data at downloading and uploading when the power level of the artificial interference is changed. The average PHY rate is calculated from the frame length.TP_{UDP}, R, N_{ALL} are the UDP throughput, the retransmission rate, and the total number of frames, respectively, and are given as follows.

$$TP_{UDP} = \frac{N_{ACK} \times 1472 \times 8}{T_{ALL}} \, [\text{bps}] \tag{1}$$

$$R = \frac{N_{NACK}}{N_{ALL}} \times 100 \, [\%] \tag{2}$$

$$N_{ALL} = N_{ACK} + N_{NACK} \tag{3}$$

16[µs]	4[µs]	2[oct]	24[oct]	8[oct]	Up to MTU[oct]	4[oct]	6[bits]	x[bits]
PLCP Preamble	PLCP Header		MAC Header	LLC Header	IP Packet	FCS	Tail	Pad

Fig. 4: Data Frame Format of IEEE 802.11a

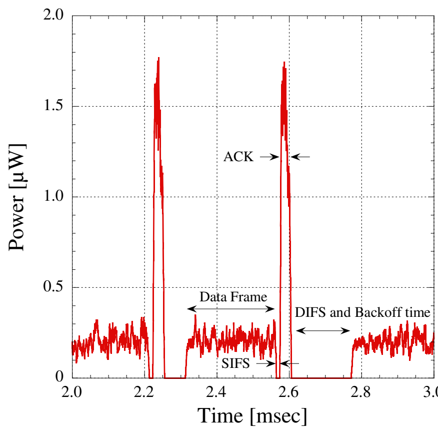


Fig. 5: An Example of Detected Wave Pattern

TABLE VI: Specifications and Data Frame Length (1500bytes) of IEEE 802.11a

PHY Rate (Mbps)	Secondary Modulation	Primary Modulation	Code Rate	Data Frame Length(μs)
6	OFDM	BPSK	1/2	2072
9	OFDM	BPSK	3/4	1388
12	OFDM	QPSK	1/2	1048
18	OFDM	QPSK	3/4	704
24	OFDM	16-QAM	1/2	536
36	OFDM	16-QAM	3/4	364
48	OFDM	64-QAM	2/3	280
54	OFDM	64-QAM	3/4	248

where N_{ACK} and N_{NACK} are the number of data frames with and without following ACK frame, respectively and T_{ALL} is the measurement time.

We do not use iperf3 for measuring UDP throughput because iperf3 keeps measuring the UDP throughput during the adjustment of artificial interference. We have to distinguish UDP throughput while the artificial interference is active. We use time versus power detected by spectrum analyzer because we can pick up only the measurement result under the active artificial interference. The channel occupancy rate (COR) is also defined as follows.

$$R_{BUSY} = \frac{T_{BUSY}}{T_{ALL}} \times 100\,[\%] \tag{4}$$

where T_{BUSY} is the time duration occupied by WLAN system. R_{BUSY} indicates the exploitation of channel by the WLAN system.

C. Measurement Results

1) Artificial Interference with 0.1 msec Idle Time: Figure 6 shows the measured performance of WLAN under the artificial interference with 0.1 msec Idle Time. The access from AP to STA is constructed, that is download. The horizontal axis is the transit power of artificial interference. As we explained, in this artificial interference, the packet collision between the packet from WLAN system and the artificial interference occur, every time. Since $100 - R$ % is the successful rate even under the packet collision, it indicates the capture effect. Therefore, $R = 0$ % means the capture effect is perfectly active.

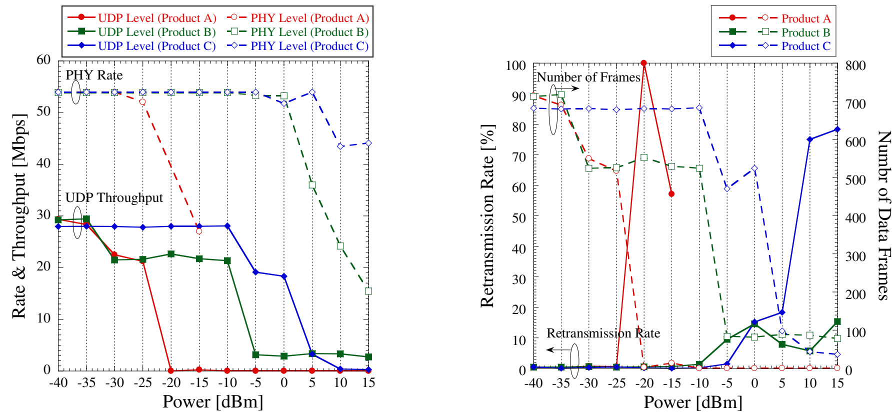
In product A, as the transmit power of artificial interference is larger than -20 dBm, the UDP throughput becomes 0. In addition, the total number of frames becomes 0 and the retransmission rate is high level. Therefore, the acceptable level of interference transmit power is smaller than -20 dBm.

In product B, the UDP throughput is maintained over 0 as the transmit power of artificial interference is from -40 dBm to 15 dBm. As the transmit power of artificial interference is larger than -5 dBm, the retransmission rate is around 10 %. Since the PHY throughput is reduced, the rate adaptation is active for securing the robustness to the interference. Since the product B has the directional antenna, the large transmit antenna gain is obtained. The product B has higher robustness to the artificial interference than the product A owing to large antenna gain and rate adaptation.

In product C, as the transmit power of artificial interference is larger 10 dBm, the UDP throughput becomes 0. The retransmission rate approaches 80 %. The PHY throughput is around 45 Mbps. From these results, the rate adaptation of product C cannot recover the degradation of link quality. If the lower level MCS set is selected like product B, the retransmission rate could be decreased and the UDP throughput could be over 0.

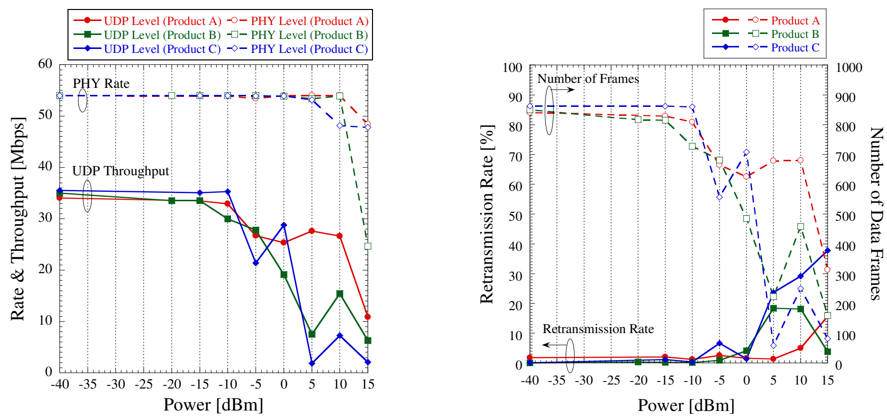
From the results, we confirm the difference of robustness to the co-channel interference among the products in transmission side.

Figure 7 shows the measured performance of WLAN under the artificial interference with 0.1 msec Idle Time. The access from STA to AP is constructed, that is upload. From this figure, as the transmit power of artificial interference is 0 dBm to 15 dBm, the UDP throughput with product A is largest and the second largest UDP throughput is product B. Since the product A has two diversity antenna, the selection or the combination diversity gain is effective for maintaining the large signal power to interference plus noise power. In addition, the retransmission rate of product C is larger than that of product B. Since the product C has built-in antenna,



(a) UDP Throughput and PHY Rate (b) Retransmission Rate and Number of Frames

Fig. 6: Result of Interference with 0.1 msec Idle Time (Download)



(a) UDP Throughput and PHY Rate (b) Retransmission Rate and Number of Frames

Fig. 7: Result of the Interference with 0.1 msec Idle Time (Upload)

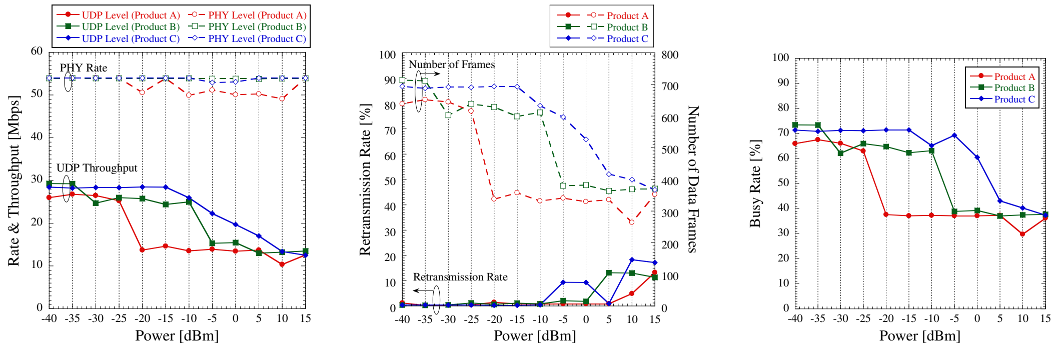
it cannot obtain the large receiver antenna gain. In addition, as the transmit power of artificial noise is 15 dBm, PHY throughput with product C is around 47 Mbps. Even though the retransmission rate is around 40 %, PHY throughput is not downgraded. Therefore, the rate adaptation is not suitable for the artificial interference.

From these results, the difference of the robustness to the co-channel interference among products is also confirmed in the reception side of product.

2) Artificial Interference with 2.072 msec Idle Time: Figure 8 shows the measured performance of WLAN under the artificial interference with 2.072 msec Idle Time. The access from AP to STA is constructed, that is download. In this experiment, we evaluate the sensitivity of carrier sense in each product. In the upload that is the access from STA to AP, the transmitter is STA. Since STA uses the common product, the sensitivity of carrier sense is equal, which we have confirmed it by experimental evaluation. Therefore, the results in upload are not shown.

The UDP throughput with product A becomes half as the transmit power of artificial interference is larger than -20 dBm. The busy rate is about 40 %. We also confirm the similar tendency of product B as the transmit power of artificial interference is larger than -5 dBm. Since the product A has diversity antenna, the sensitivity of carrier sensing is enlarged owing to the large diversity gain. In the product C, as the transmit power of artificial interference is between -5 dBm and 0 dBm, the retransmission rate is 10 % and the busy rate is maintained in high level. Therefore, the product C is under the condition of hidden node terminal because the sensitivity of carrier sensing is not high.

From these results, we confirm the difference of sensitivity of carrier sensing among products owing the different configuration of antenna.



(a) UDP Throughput and PHY Rate

(b) Retransmission Rate and Number of Frames

(c) Busy Rate

Fig. 8: Result of the Interference with 2.072 msec Idle Time (Download)

IV. Conclusions

This paper evaluated the performance of robustness to the co-channel interference in commercial products of wireless local area networks (WLANs). We confirmed the difference of capture effect and sensitivity of carrier sensing among the products owing to the configuration of antenna and the function of rate adaptation. The difference performance of robustness to co-channel interference decides the sharing condition of frequency spectrum. If the products have high robustness to it, these are suitable to share the common channel because the mutual interference between them are under controlled. Otherwise, these access to the different channel for avoiding the mutual interference. It is an important future work to select the channel selection in accordance with the performance of robustness to co-channel interference.

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