Measurment and Analysis on QoS of Wireless LAN Densely Deployed with Transmission Rate Control

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Abstract— **This paper investigates Quality of Service (QoS) of the personal mobile wireless LANs (m-WLANs). The situations in the m-WLANs differs from the situations in the normal use of WLANs; the access point (AP) and the associated terminals (TEs) are in proximity. In the m-WLANs, the *capture effect* (CE) significantly affects on the throughput performance. To measure the impact on the QoS by the CE, the experimental study considering the interference from other power sources (APs and TEs) are required. However, since it is difficult to understand the detailed relationships between the QoS factors, the analytical calculations were also performed. With the experimental and analytical results, we demonstrated that the auto rate fallback algorithm of WLAN causes degradation of the QoS performance. We propose two transmission rates controlling schemes to improve the QoS performance.**

Keywords—interference, WLAN, transmission rate, capture effect, performance anomaly, mobility, portable, dense

I. INTRODUCTION

Recently, the personal mobile wireless LANs (m-WLANs), which use IEEE802.11 technology and consist of light weight battery-operated mobile access points (APs) and a small number of connected personal devices or terminals (TEs) such as smart phones are becoming popular. As a result, there are some cases in which many WLANs are densely deployed in a place (e.g. in the crowded meeting and in cafe). Moreover, the situations in the m-WLANs differ from those in the traditional use of WLANs ; that is, the AP and the associated TEs are in proximity.

Thus, this paper investigates there is a possibility that Quality of Service (QoS) performances in all the m-WLANs are degraded due to interference from the multiple WLANs that share the same frequency channel.

When there are many WLANs in close proximity, it is impossible to operate only on the non-overlapping frequency channels for all WLAN. If many m-WLANs share the same channel, many collisions occur between the TEs for operating on the same collision domain. When the AP and the associated TEs are in proximity, the data frames can be successfully received in each WLAN by *capture effect* (CE), even if the collision occurs. Actually, CE occurs if the signal to the interference ratio (SIR) is larger than a specific value. Since the distances between APs and TEs in the m-WLANs are much shorter than the distance between the m-WLANs, CE often occurs in the case of collisions between m-WLANs. This results in parallel transmission and throughput improvement. It is shown later that the total throughput can be larger than a capacity of the channel or throughput in the traditional use of the WLANs because of the parallel transmission. In order to maximize a merit of the parallel transmission, it looks better to increase the number of m-WLANs. However, the increase of the number of m-WLANs causes SIR degradation. The degradation of the SIR weakens CE and decreases the total throughput. Thus, for the number of m-WLANs, there is a trade-off on the total throughput in m-WLANs between the improvement by the CE and degradation by the SINR decreasing. Moreover, in WLAN, it is well-known that the throughput is unnecessarily reduced by the auto rate adaptation (ARA) and also by *performance anomaly*.

Therefore, we have to care about two features on the total throughput of m-WLANs as follows.

(1) The tradeoff between the throughput improvement by the CE and the throughput degradation by the increase of the interferences with the increase of the number of the WLAN
(2) The effect of the CE and the ARA that also cause the total throughput improvement and degradation in m-WLAN, respectively

Analytical calculation results alone cannot necessarily indicate the QoS performance in reality, while only experimental results with the real devices also cannot explain the details and relations between those factors described above. Therefore, we demonstrated both the calculations and the experiments to show the reliability of both.

Thus, in this paper, evaluations are performed for the CE and the performance anomaly, and the ARA. Then two transmission rates controlling schemes are proposed to improve the QoS performance; i.e., (1) fixed transmission rate scheme and (2) limiting traffic amounts scheme. It is confirmed that both schemes improve the total throughput performance in m-WLANs.

II. TECHNOLOGIES AND RELATED RESEARCH

A. Multi Transmission Rate

The multi-rate of IEEE802.11 is well-known to cause performance anomaly in throughput. Many researches take account of the multi transmission rates in WLANs [1]. In densely deployed WLANs, performance anomaly of a WLAN could widely spread over the rest of all the WLANs which are in the same collision domain. In the case, only a TE that sends with a low transmission rate which would cause performance anomaly in the WLAN of the terminal also could cause performance anomaly in all other WLANs. Multi-rate effects on multiple WLANs have not been analyzed yet in detail. A research [4] investigated total throughput in many WLANs located in a carrier sense range. It also revealed relations between the number of terminals in a WLAN and performance for the number of WLANs. It also shows the reasons why the relations are made. However, the research does not mention about how CE shows such performance characteristics.

This paper will try to reveal to what extent total throughput increases when the number of WLANs increases with different distance between WLANs and different transmission rates.

B. Frame Error and ARA

ARA implemented in a real machine automatically reduces transmission rate based on transmissions rate or event of frame error [1]. In general, transmission rate should not be reduced in the case of congestion but should be reduced in case of signal being weak. In other words, if SIR is small, transmission rate should not be reduced. On the other hand, if Signal to Noise Ratio (SNR) is small, transmission rate should be reduced. However, in general, almost all real machines have no function to know the reason behind a frame error. Thus, ARA algorithm always reduces transmission rate when transmission is not successful regardless of the reason. This may cause unnecessary and serious performance degradations or performance anomaly when the reason results from congestion, i.e. low SIR. Algorithm of ARA is not standardized, and in general, it is not disclosed by vendors of MAC function implementation.

C. Capture Effects and Performance Anomaly

CE is defined as an effect where a strong signal win over weak noises/interferences. CE is likely to occur when the Signal to Interference and Noise Ratio (SINR) is high. When a frame is received successfully with the SINR being more than the threshold, the SINR value is called the SINR threshold and the value depends on the transmission rate. The SINR threshold at low transmission rate is smaller than that of high transmission rate. This is because low transmission rate is stronger than high transmission rate against noise/interference.

Performance anomaly with multiple WLANs occurs as follows. when a transmission rate of certain WLAN is dropped within a range of CSMA channels shared by many WLANs, the WLAN of low transmission rate takes a long transmission time due to equal opportunity of CSMA/CA mechanism. WLANs of high transmission rate have to wait for a long time. Thus, low throughput is observed over all WLANs regardless of high transmission rates.

In the case of WLANs sharing a CSMA/CA channel, the number of frames that collide is increased as the number of WLANs is increased. As mentioned before, the frame is successfully received by CE, that is, by the condition that the SINR is more than the SINR threshold. Interference value is proportional to the number of the collided frames. Thus, CE becomes weaker and frame errors increases when the number of WLANs is increased. The frame errors could invoke ARA and could result in performance anomaly. A related study evaluated CE and performance anomaly under condition that the distance between AP and terminal is far[10]. Impact of CE has not been investigated well in densely deployed m-WLANs[12].

D. Collision and Paralell Transmission

When a collision occurs, the frames of the collision is received as in one of the following three cases; (1) all frames of the collision become error frames, (2) only one frame is received correctly, and the other frames is not received, and (3) multiple frames are received correctly, and the others become error frames. The following situations or conditions explain how the cases occur. (1) A condition that an AP receives multiple frames at the same time with the almost same powers. (2) A condition that an AP receives multiple frames of different powers. Under this condition, a frame of the largest receiving power is only successfully received, but the others are not received at all. (3) A condition that more than two APs receive frames from their associated TEs, and some of the APs can obtain CE. For example, there are more than two WLANs, and each WLAN sends a frame at the same time. When the SINR in a AP is larger than SINR threshold, the AP correctly receives the frame. This is likely to occur in the case of m-WLANs where an AP and associated TEs are much more nearly located than m-WLANs are located. If more than two WLANs frames are successfully received, parallel transmission is achieved in even CSMA/CA. Eventually, the maximum numbers of parallel transmission could be the same as the numbers of m-WLANs.

Possibility of parallel transmission is increased by strength of CE. CE can become strong when a distance between an AP and associated TEs in a m-WLAN is short, and a distance between m-WLANs is long.

Performance evaluation that takes CE into account in m-WLAN are still few although that in fixed WLAN are many. Studies on control to carrier sense threshold and CE on fixed-WLAN are summarized in [2]. For fixed WLANs, control to carrier sense threshold and CE seems to be easy since they can be well planned. However, for m-WLANs, such control seems to be difficult because many conditions such as interference strength are likely to change from time to time. There are many different control methods in which carrier sense threshold and transmission power are autonomously or simultaneously changed [3, 5]. They achieve fair utilization of radio resources by controlling carrier sense threshold and transmission power. However, cumulative interferences from different WLANs are not considered in their evaluation model.

The control methods have considered CE as well as parallel transmission. Parallel transmission is very attractive behavior in multiple WLANs because parallel transmission could give WLANs much higher throughput than link capacity of one channel. This paper considers cumulative interferences and CE for evaluating throughput of densely deployed m-WLANs. Real machines should be employed for the evaluations because CE is affected by not only received signal strengths but also by processing gain of the received signals.

III. QoS Characteristics in Densely Deployed WLANs

In this paper, it is again assumed that an m-WLAN consists of a few TEs, for example, two or three TEs, and they are closely placed, i.e. a distance between an AP and associated TEs is very short, for example, within reach of hands. This is because mobile users are assumed to take their portable APs and a few devices such as smartphones, laptop PCs and tablets together with them. When such mobile users meet in a place such as a café and a meeting room, many m-WLANs have to share the same channel. Total throughput of the channel used by the m-WLAN in such a situation will be evaluated in this paper. First, improvement factors and reduction factors for the throughput are discussed in the following subsections.

A. Improvement Factors

By parallel transmission, throughput can be improved. Gains by parallel transmission increase as the number of WLANs increases. Thus in order to get parallel transmission gains, it is better to have as many numbers of WLANs as possible.

By CE, the parallel transmission is achieved. Thus, in order to obtain parallel transmission gain, it is necessary to obtain CE. CE has more gains when a ratio of a distance between TEs in a WLAN over that between the WLAN and other WLANs is larger in which radio propagation condition is the same over the TEs. Thus, as WLANs are farther located, located, CE can be more obtained.

B. Reduction Factors

By cumulative interference, CE cannot be obtained. When many WLANs send frames at the same time and cause collisions, probability of collisions can be high and interference is cumulative by a numbers of collision frames. SIR could become small when many WLANs send frames. This results in frame errors. Frame errors can invoke ARA mechanism and cause performance anomaly. Thus as the number of WLANs increases, throughput could be reduced.

Based on all the above improvement and reduction factors, it is estimated that throughput can increase at the beginning as a number of WLAN increases, but decrease at last. In other word, throughput can have a maximum value to the number of WLANs.

IV. Total Throughput Analysis of m-WLAN

In this section, we show the analytical and experimental results of the relation between the number of the m-WLANs and the total throughput when many m-WLANs are densely deployed.

A. Analytical Results

The effects of the CE and the SINR on the total throughput performance are evaluated by analytical calculations. Only one frame from each WLAN is assumed to be sent at the same time. The condition of the CEs is described in Eq. (1) [7].

$$\frac{P_d}{N_0+\sum_{k=1}^{n} P_k} = \gamma > z_0 g(S_f) \tag{1}$$

where, P_d is the power level of the received signal, *n* is the number of the interfering m-WLANs, and P_k is the power level of the *k*-th received interfering m-WLAN. z_0 is the capture ratio and $g(S_f)$ is the processing gain of the interfering signals.

The capture probability in the infrastructure mode without the power control is described in Eq. (2) [8].

$$P_{cap}(z_0 g(S_f)|i) = \text{prob}\left(\gamma > \frac{z_0 g(S_f)}{i}\right) = \prod_{i=1}^{n}\left(1 + z_0 g(S_f)\frac{p_{0i}}{p_{0u}}\right)^{-i}, \tag{2}$$

where, p_{0u} is the local output power level of the interesting m-WLAN terminal and p_{0i} is the local output power level of *i*-th the interfering m-WLAN terminal. d_0 is the distance between the AP and the TE within a m-WLAN and *d* is the distance between m-WLANs. The frame capture probability is

$$P_{cap}(z_0, n) = \sum_{i=1}^{n-1} R_i \cdot P_{cap}(z_0 g(S_f)|i), \tag{3}$$

where, R_i is the generating probability of *i* interfering frames at an time slot and describes in Eq. (4).

$$R_i = \binom{n}{i+1}\tau^{i+1}(1-\tau)^{n-i-1}, \tag{4}$$

where, τ is the probability that a TE starts a transmission in a randomly chosen time slot [9]. The collision probability is

$$P_{col} = 1-(1-\tau)^{n-1} - P_{cap}(z_0, n), \tag{5}$$

The probability that there is at least one transmission in the considered time slot, with *n* contending for the channel, each transmitting with probability τ is

$$P_{tr} = 1-(1-\tau)^{n}, \tag{6}$$

The conditional probability that a packet transmission occurring on the channel is successful is

$$P_s = \frac{n\tau(1-\tau)^{n-1} + P_{cap}}{1-(1-\tau)^{n}}, \tag{7}$$

The probability of erroneous frame delivery within the retry limit [9] is calculated by

$$P_e = \left(1-\left(1-P_{e,data}(E[PL],SNR,M)\right)\left(1-P_{e.ack}(SNR,M)\right)\right)^m \quad (8)$$

where, $P_{e,data}$ and $P_{e.ack}$ are the data error probability and the ACK error probability, respectively. m is the maximum backoff stage number, $\mathrm{E}[PL]$ is the average payload length, and M is the IEEE 802.11g PHY mode.

Thus, a WLAN's throughput is calculated by

$$\mathrm{S} = \frac{E[payload\ transmitted\ in\ a\ timeslot]}{E[length\ of\ a\ timeslot]}$$

$$= \frac{P_{tr}P_s(1-P_e)E[PL]}{(1-P_{tr})\sigma + P_{tr}(1-P_s)T_c + P_{tr}P_sP_eT_e + P_{tr}P_s(1-P_e)T_s}, \quad (9)$$

where, σ is the duration of an empty time slot. T_c, T_e and T_s are the average times that a channel is sensed busy due to a collision, error affected data frame transmission time and successful data frame transmission times, respectively. They can be computed as follows.

$$T_c = T_e = [MAC\ header] + \mathrm{E}[PL] + [ACK\ timeout]$$
$$T_s = [MAC\ header] + \mathrm{E}[PL] + \mathrm{SIFS} + \mathrm{ACK} + \mathrm{DIFS} + 2\tau_d, \quad (10)$$

where, τ_d is the transmission delay. In this paper, since the maximum transmission distance is about 7 m, τ_d can be neglected. The values of MAC header, ACK timeout, SIFS, ACK, and DIFS are employed from typical values of IEEE802.11g.

The numeric results of this analysis are used in the next section to validate the experimental results with real devices.

B. Throughput Evaluation by Real Machine Experiments

This section describes comparison of the results by the analytical calculations and the experiments with real devices in order to show the reliability of the analytical results. Since the calculation does not consider EIFS, the total throughput result by the calculation is considered to be better compared to the result by the experiment. The experiment was performed without the ARA to compare with the calculation.

The configurations of the experiments are following.

It measured the total throughput and the frame re-transmission rates of 16 WLANs. A WLAN consists of an AP and a TE. The real devices used in the experiments are the pocket router (PLANEX MZK-MF300N [13]) as the AP and the Android mobile terminal (Google Nexus S [14]) as TE. The throughput measurements were performed by the IEEE 802.11g UDP uplink using iperf [15]. The TE sends UDP traffic which does not include any upper layer protocol (e.g. the congestion control protocol as in TCP). Uplink communication was used because the throughput of the downlink communication does not change with the number of TEs. The experiments measured the throughput of m-WLAN at a meeting room in the Ochanomizu University (located at Bunkyou-ku, Tokyo, Japan). Though several WLANs other than the experiment's WLAN were detected, their effects on the measurement were supposed to be negligible because

(1) The measured throughput reached 23Mbps, which is usually monitored without any interferences, and

(2) There was very little actual traffic from the other WLANs on the results acquired with the packet capture device, AirPcap [16].

The configuration of the throughput measurement is shown in Fig. 1. Each WLAN was located on the rectangular grid. The distance, d, between WLANs was set to 30cm and 1.0m and the distance between AP and TE within a WLAN was set as close as possible, for example, 5cm.

The total throughput dependence on the number of WLAN is shown in Fig. 2. The maximum total throughput of 33.6Mbps was obtained when 7 WLANs. When the number of WLAN was larger than 7, the total throughput decreased because the SINR decreased and the number of the collision errors increased. This trend is well accorded with the calculation results as shown in Fig. 2.

Therefore, the experimental results are considered to be reliable.

So far, the evaluation was done without ARA. Most of all real devices use ARA by default. Thus, evaluations should include ARA effects. The experiment is more preferable than the analytic calculation to evaluate ARA effects because it is difficult to accurately make analytic models of ARA implemented in real devices. In the next Section, evaluations include ARA and thus hereafter real device experiment will be employed.

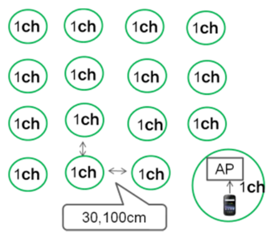

Fig. 1 m-WLAN layout

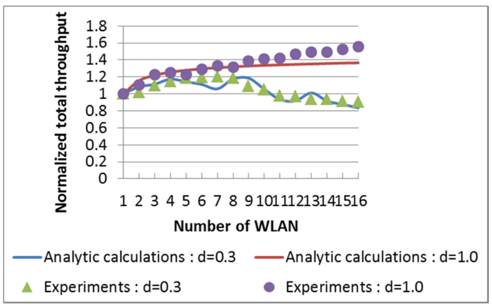

Fig. 2 Numbers of m-WLAN and total throughput by analytic calculation and by real device

V. Proposed Contorl Schemes and Evaluation Results

Control schemes to improve the total throughput of m-WLANs are proposed for large numbers of WLAN. Two proposed control schemes are described, and then the experimental results for both of them are shown. Though the direct reason of the throughput reduction is collision error due to small SIR, the performance anomaly due to ARA invoked by the collision error are also supposed to severely decrease the throughput as explained in Section II. Therefore, efforts are required to alleviate or avoid both collision error and performance anomaly.

The first control scheme is to fix the transmission rates with higher values, and the second control scheme is to limit the traffic amount. If all the WLAN deploy the first control scheme, the total throughput of m-WLAN can be significantly improved. However, there can be APs and TEs that cannot fix their transmission rates in real devices. In such cases, the second control scheme can be applied. Since the second control scheme limits the traffic amount of only WLANs which potentially cause the performance anomaly, the performance anomaly is expected to be alleviated and the total throughput of m-WLANs can be improved.

A. Fixed Transmission Rate Control Scheme

The first scheme [11] is described as follows. First, it is shown that ARA causes serious performance degradation in densely deployed m-WLAN. In Fig.3, a curve with triangle spot is a measured total throughput. The measurement configuration was the same as shown in Fig.1. Only one terminal at each number of WLAN is set to use ARA and the rest is to be fixed in transmission rate.

As the number of WLAN increased, the throughput also increased at first because of parallel transmission and achieved more throughput than that of one WLAN. When 6 WLANs, the throughput was maximized. Then, the throughput steeply decreased as the number of WLAN increased from 7 to 10 because of the degradation of the SINR. In detail, the degradation of the SINR caused the frame errors at the collisions and caused the retransmissions. Then, ARA reduced transmission rate which results in performance anomaly. Only one ARA WLAN caused such significant performance degradation.

The proposed scheme, fixed transmission rate control scheme is simple enough but very effective. In the scheme, each m-WLAN must fix its transmission rate to its own highest rate. In other word, it is to turn off ARA. The reason why the scheme is effective is that frame errors are likely to occur not by small SNR but by small SIR in m-WLAN case. Thus, transmission rate should not be reduced. Compared with ARA, the scheme will provide better utilization of frequency resources. Moreover, since the scheme weakens effects of performance reduction factor, the improvement factor, CE, can improve the total throughput more.

Figure 3 also compares the proposed fixed transmission rate control scheme with ARA. The curve of the proposed scheme is marked with square spot. The total throughput is supposed to increase more as the number of the WLANs increases. After the maximum throughput at 7 WLANs, the throughput gradually decreased but not steeply decreased. The frame error due to collision and degradation of the SINR still brings negative impact on the throughput performance. However, the results show that the first control scheme significantly improves the total throughput compared to the previous case without the control. The maximum improvement 73 % was achieved at 16 WLANs compared with the case using the same number of WLANs with only one ARA WLAN. This significant improvement was achieved because the control scheme avoids the performance anomaly.

The total throughput of m-WLANs is shown in Fig.4 when the distance between m-WLANs is 30cm and 100cm. Though each WLAN has only one TE in the experiments, the improvement of the total throughput can be achieved even with multiple TEs within a WLAN. When the number of TEs increases, the frame errors caused by the collision may increase. However, since it is not necessary to decrease the transmission rates even in this case.

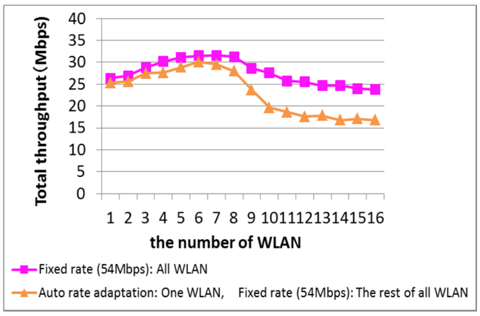

Fig. 3 Comparison between fixed rate only and all fixed except one ARA.

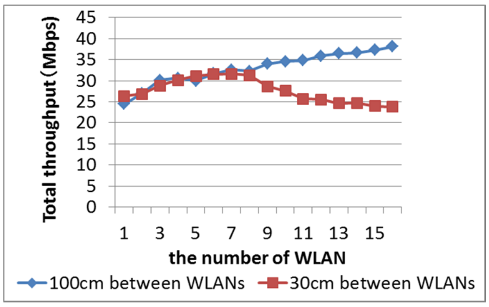

Fig. 4 Throughput for all 54Mbps WLANs for different distances

B. Traffic Amount Limitation Control Scheme

Second control scheme is traffic amount limitation control scheme. It limits traffic amounts of ARA WLANs. The advantages of the proposal are that it can be used when not all the WLAN can operate with fixed transmission rate, i.e. with turning ARA off.

First, different configuration of ARA WLAN was evaluated. The measurement configuration was the same as shown in Fig.1. The distance between WLANs was set to 100cm. One WLAN deploys the ARA, and the transmission rates for other WLANs were set to 54Mbps. The total throughput of this setting degraded 30% compared to the case where the transmission rates for all the WLAN were fixed to 54Mbps in Fig. 5 at 16 WLANs.

Figure 5 also shows the traffic amount limitation control scheme could improve total throughput. In the control, traffic of ARA WLAN was limited to 10Mbps. By the control, throughput degradation is alleviated compared to the case without control. The throughputs in the proposed scheme at 16 WLANs are 97% of that in all fixed WLAN case which is the same as in the first control.

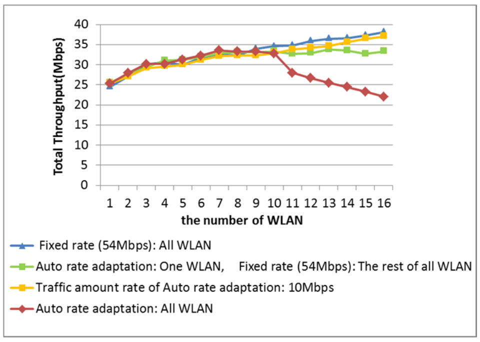

Fig. 5 Traffic amount control scheme with the sending rate of 10 Mbps

VI. Conclusion

Characteristics of the total throughput, with respect to the increase of the number of the WLANs, are determined only by the degree of influence of the following two features, in the case of densely deployed WLANs. (A) The total throughput of WLAN increases by the parallel transmission caused by *capture effect*, when collisions occur, (B) The total throughput of WLAN decreases by the frame error caused by SINR degradation due to collisions.

Theoretical analysis and experiments are employed to confirm the throughput performance described above. They demonstrated that the total throughput of the densely deployed WLANs significantly degrades by the performance anomaly when the frame error occurs.

In order to improve the throughput, two control schemes are proposed; (1) Fixed transmission rate scheme, and (2) Traffic amount limitation control scheme. The proposed two schemes are evaluated by the experiments and they improved the total throughput of WLANs 73% and achieved 97 % of ideal throughput.

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