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Context Aware Multi Rate Control in Densely Deployed IEEE802.11 WLAN for Avoiding Performance Anomaly

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***Abstract*— In this paper, QoS characteristics such as TCP throughput is investigated for densely deployed mobile wireless LANs (WLANs). Factors affecting throughput characteristics are discussed and evaluated by using real machines such as smartphones and portable APs. In IEEE 802.11 WLANs, a rate adaptation mechanism controls the transmission rate and one of the dominant factors for QoS. In order to understand the behavior of the rate adaptation control, 1 to 18 sets mobile WLANs are examined under different parameters. Since a behavior of the rate adaptation control is a vender specific one and it strongly depends on interference, signal strength and etc., the real terminals such as smartphones were used in the experiments. *Performance anomaly* drastically reduces the throughput not only in the WLAN which has a terminal with low transmission rate but also in the neighboring WLANs that share the same channel. In order to avoid unnecessary transmission rate degradation by the rate adaptation control, Context Aware multi Rate Control (CARC) is proposed and evaluated. In CARC, Turning the rate adaptation control on/off is controlled according to a context, for example, signal strength. The evaluation results show that the CARC can be cost-effectively implemented and improves the throughput performance of whole WLANs by 3.5 times than that without the application of CARC.**

Keywords*— WLAN; Wireless LAN; Mobile; Content aware; Throughput; QoS; Interference; Collision; Rate adaptation; Auto Rate Fallback; Rate adaptation contol; Performance anomaly; Capture effect.

I. Introduction

IEEE 802.11 based wireless local area networks (WLANs) have seen rapid deployment over the last decade, and are now a critical part of the wireless infrastructure in both residential and enterprise settings. Buoyed by the increasing base of Wi-Fi enabled consumer devices and the explosive growth in mobile data demand, there has been a recent emergence of a new form of WLAN in which the access point (AP) itself is a mobile device. Such mobile wireless LANs (WLANs), alternative termed as mobile hotspot networks, MiFi networks [1], or Wi-Fi tethered networks, are expected to grow over 400% in the next three years [2]. Mobile WLANs are composed of small form-factor mobile APs (either a stand-alone device or a smartphone or tablet with tethering capability), and a small number of connected client-devices such as laptops, other smartphones, and wearable Internet devices [3]. 3G, LTE, or WiMAX based cellular networks typically provide the front-haul connection from the mobile AP to the Internet.

Due to its small form factor and portability, wide-scale adoption of mobile WLANs could lead to extremely dense deployment of APs – a conference with several attendees using MiFi like devices being a typical example. In such settings, the throughput of the WLANs, and thus the quality of service (QoS) delivered to the users could be severely degraded due to interference and bandwidth sharing. The extent of degradation would evidently depend on both the physical distance and the situation of mixture of various bit rates. It is also necessary to consider throughput characteristics when many WLANs densely located use a certain channel combination. There could be several WLANs that use the same channel. This is because both a number of WLANs are more than a number of available channels and each AP selects a random channel regardless of other AP does.

This paper investigates the effects of *performance anomaly* due to radio signal interferences and multi rate adaptation in physical transmission rate on QoS characteristics of mobile WLANs by using commercial mobile APs and clients. This work is informed by the large pool of existing literature on fixed WLAN systems, and this research contributes towards extending the findings in the mobile WLAN environment. Mobile WLANs differ from

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fixed WLANs in terms of two key characteristics: (i) mobile WLANs typically consist of a small number of clients (between 1 and 5) which are located very close to the mobile AP; (ii) mobile WLANs exhibit a much more dynamic nature of interference due to the mobility of the AP. Moving APs might go in and out of range of multiple fixed APs or other moving APs. A number of fixed and moving APs that contributes the interferences usually dynamically varies. In contrast, enterprise/hotspot management techniques have to typically deal with a large number of spread out clients, and the dynamism is largely due to changes in load rather than movement of APs.

In terms of sharing the same channel, the QoS characteristics of mobile WLANs have been investigated in a few recent works [4-8]. These studies focus on analyzing throughput characteristics of two WLANs when distance between them is varied. The results indicate interference which reduces the throughput also affect more than two WLANs densely located. In addition, when a number of terminals that participate to CSMA/CA increases, probability of contention or collision increases. This leads to further degradation in the performance. Especially, if a terminal uses auto rate adaptation or multi-rate adaptation control [9-12][18][20][21], the situation becomes much worse because of nature of multi-rate and sending opportunity fairness in CSMA/CA or *performance anomaly* occurs so that throughputs of all WLANs are forced to decrease. Thus, this paper aims to investigate throughput characteristics of densely deployed mobile WLANs with and without consideration of the *performance anomaly*. A simple but effective rate adaptation control, Context Aware multi Rate Control (CARC) is also proposed and evaluated. In order to capture from physical layer factors such as *capture effect* to MAC layer factors such as collision, real machines of APs and terminals were used in the evaluations in which from 1 to 18 sets of real WLANs are used.

This paper is organized as follows. Section 2 discusses related works and explanation of key technologies; *performance anomaly* and rate adaptation control. In Section 3, factors affecting QoS characteristics of densely deployed mobile WLANs are discussed with experimental evaluations. Throughput degradation by low transmission rate caused by rate adaptation control is discussed in Section 4. In Section 5, CARC is proposed and evaluated to show improvement in throughput, followed by the conclusion in Section 6.

II. BACKGROUND

A. Related Works

Considering interference, many researches have tried to effectively utilize bandwidth or to improve QoS of IEEE802.11 WLANs in a variety of different settings, for example, in multi-hop networks [11], and in the context of handovers [12][13]. They revealed interference between WLANs reduces SINR and then decreases capacity for whole WLANs in the same channel. They also proposed various solutions. For example, emission power adaptation methods, beam forming technologies, AP location designs, and cooperative mechanisms. However, they do not consider the situation in which many densely deployed mobile WLANs exist. In the situation, much more interference is expected to affect characteristics of QoS such as throughput. Mobility also makes the solutions such as emission power adaptation to be limited. Mobile WLANs present a few unique characteristics that make the interference problem even more challenging than in fixed WLANs. Power control has also been shown to be an effective solution for interference mitigation in traditional fixed WLANs [14]. However, it is difficult for power control to be applied to mobile APs because it is assumed that such mobile APs move frequently and that the associated terminals also move with them. For example, if a person is carrying a mobile hotspot device in his pocket while walking/running, the AP and the connected client devices, such as body sensors, smart-shoes, etc. all move together.

When a number of WLANs more than numbers of non-overwrapping channels exists or some portable types of APs and tethering devices have a fixed channel number, for example channel 6 is often used in US [15], and often in especially smartphone tethering can not change the channel number, many numbers of WLANs have to share the channel or have to be operated in the same CSMA/CA domain. It is imagined that such many WLANs are typically used in a conference room, a meeting room and a cafe as well as crossing on street of metropolitan area. For example, a famous sightseeing spot Shibuya Crossing in Japan [22]. In such spaces, many people bring a mobile WLAN AP and use it for a laptop PC, a tablet and smart-watch. Thus, such many mobile WLANs result in densely deployed although fixed WLAN APs are usually well planned to be enough apart located. In terms of sharing the same channel, the QoS characteristics of mobile WLANs have been investigated in a few recent works [4-8]. They have disclosed throughput characteristics of two WLANs with different distance each other. The results indicate some factors which reduce the throughput also affect more than two WLANs densely located [20]. Moreover, when a number of terminals that are associated even to different WLANs and participate to the same CSMA/CA increases, probability of contention or collision increases. This would lead another performance reduction [19]. Especially, if a terminal uses rate adaptation control or multi-rate adaptation control [9-12], the situation becomes much worse because of nature of multi-rate and sending opportunity fairness in CSMA/CA or *performance anomaly* occurs so that throughputs of all WLANs are forced to decrease.

That is why many WLANs densely deployed should be investigated. Thus, this paper is trying to understand QoS performance characteristics of densely deployed WLANs.

It is very difficult to simulate mobile WLANs for evaluating their QoS characteristics. For example, rate adaptation functions are not standardized but are proprietary implemented and not disclosed by each MAC chip vendor. In addition, interference results from several factors, such as device performance, multi-path characteristics, and equalizer performance and results in bit errors of received signals. A pure computer simulation based approach to capture such complicated nature of the interference is thus difficult. Also previous studies [13][14] have pointed out the inaccuracy of computer simulation models in reflecting a true nature of the interference in WLANs. Thus, empirical studies on real machines are required.

In this paper, throughput characteristics are investigated with numbers of WLANs, numbers of terminals in a WLAN by using real machines. Context Aware multi Rate Control (CARC) is also proposed and evaluated to improve the throughput.

B. *Performance Anomaly and Rate Adaptation*

Even when only one terminal uses a low transmission rate, throughput of the all terminals and APs sharing the bandwidth, i.e. in the same CSMA/CA domain are decreased. This is called *performance anomaly*. Especially, a combination of higher transmission rates and lower transmission rates causes severe throughput degradation in higher transmission rate terminals. For example, if a WLAN has a 54Mbps and a 6Mbps terminal, each throughput is roughly and logically calculated with a harmonic average, 1/(1/54+1/6)=5.4Mbps. This means that only 10% in throughput is obtained from 54Mbps of 802.11g capacity. This is because of even sending opportunity of CSMA/CA mechanism and multi-rate of transmission rate.

Originally, multi-rate is used for seeking better probability of success transmission by adapting any signal to interference noise ratio (SINR) environments and is implemented to a rate adaptation control. A rate adaptation control generally lets a transmission rate go down in a case of retransmissions and go up in a case of successful transmissions. However, it is difficult for the rate adaptation control to differentiate a retransmission due to poor SINR from a retransmission due to a collision. This difficulty may cause unnecessary low transmission rate. Collisions are generally likely to happen when a WLAN has many terminals or a WLAN shares a channel with other adjacent WLANs.

In a case of densely deployed WLAN, *Performance anomaly* occurs over all WLAN which are sharing the same CSMA/CA domain. In other words, when one terminal lets its transmission rate go down, all the terminals that can sense its carrier have to wait to send their frames. This means that if one WLAN is likely to have significant retransmission rate, other WLANs could be suffered by performance anomaly. This seems like *Performance anomaly* is propagated to over the WLANs.

III. Performance Characteristics of Densely Deployed WLANs

A. *WLAN Performance Evaluation Model*

For evaluations and discussions, mobile WLANs densely deployed are modeled as follows. A mobile WLAN consists of terminals and an AP. They are portable like MiFi or Tethering devices. Although through the authors' experience, many tethering-able smartphones including iPhone 4S and Galaxy S could not manually change channel number, portable devices automatically change channel number to avoid using the same channel as other devices. Here, no matter the channel number can be changed or not, several WLANs are assumed to use the same channels and share the bandwidth with CSMA/CA because many WLANs are densely deployed. In the experiments, real machines which are sold in an IT shop are used. The experiment was done in a meeting room in a building of Tokyo Institute of Technology, Japan. Radio shield rooms were not used for the experiments in this paper because it is desired to know QoS characteristics of experiment devices and radio environment including characteristics of device performance, multi-path, and equalizer performance. Some characteristics of device performance used in this paper were already measured in a radio shield room and are disclosed in [16]. In order to share the same bandwidth with CSMA/CA, all WLANs in concerns were kept within 4 m area. Carrier signals spread 4 m with enough strength.

Throughput of uplink TCP traffic is employed as a performance measure. All the mobile terminals send TCP traffic toward a receiving terminal via AP.

Note that physical layer capacity such as 54Mbps consists of MAC throughput and MAC overhead and physical layer overhead. MAC overhead includes MAC ACK, back off, MAC frame retransmission and so on. MAC throughput consists of TCP throughput and TCP ACK overhead. Since TCP throughput depends on packet loss rate and round trip time (RTT), RTT is set to be ignorable small. Packet loss other than in WLANs does not occur except at AP buffers.

B. *Measured Throughput and Factors Affecting Throughput*

Several main factors affecting throughput performance are here explained. TCP Packet losses occur by a retry out loss and buffer overflow in a AP buffer. Since retry out results from more than a certain number of MAC successive retransmissions, for example, 7 times of retransmissions, it rarely occurs. On the other hand, buffer overflow easily happens when conditions are met. In the evaluation model, a AP buffer for downlink is shared and used for the terminals.

As a numbers of the terminals increases, probability of buffer overflow increases. Competition to seize a buffer becomes severe as more numbers of terminals use the buffer. Many simulation results with small buffer with error free assumptions show unfairness of TCP throughput of uplink traffic. However, error does occur in real and in the experiments, and buffer size is not so small even in portable APs. For long term, AP buffer are fairly used and throughput does not show unfairness. On the other hand, a number of active terminals affects TCP throughput characteristics. An active terminal is defined as a terminal which has backlog packet to send. A terminal which waits for TCP ACK and can not send any more TCP data packet is not an active terminal. When a terminal sends TCP data and exhausts its congestion window, it has to stop sending data and wait for TCP ACKs. Generally due to unfairness of uplink and downlink in WLANs, APs are likely to have backlog and to be active terminals, especially with TCP traffic. Only active terminals contribute collisions. Thus, a number of active terminals affects MAC throughput and then TCP throughput.

Capture effect is an effect in which a MAC frame having stronger signal against noise wins and gets successful transmission in case of collisions [21]. In mobile WLANs, parallel and successful transmission can be achieved if capture effect is effectively obtained. This happens on only collisions between WLANs. Especially, WLANs have large distance between WLANs and AP and terminals in a WLAN have small distance, for example, 1 m and 0.1 m, respectively. This nature shows interesting characteristics. More numbers of collisions occur, higher throughput is obtained [20].

Rate adaptation control can be a dominant factor of throughput characteristics. As rate adaptation control in a real device has a vender specific algorithm which is not disclosed, the implications of input and output of rate adaptation control is used. In other words, rate adaptation control can be error sensitive if transmission rate is decreased as error rate is increased. When rate adaptation control decreases transmission rate, it causes *performance anomaly* and throughput is drastically reduced.

C. *Measured Results*

The experiment was done with turning rate adaptation control on of all the terminals and the AP. Smartphones, NEXUS S and Galaxy S were used as the terminals and a tiny AP, Planex MZK-MF300N was used as the AP. All APs used explicitly 802.11g. WMM (802.11e, EDCA) was not used. All the terminals sent uplink TCP traffic to a receiving terminal via the AP. Each WLAN was located with variable from 0.05 m to 1.0 m distance each other in lattice topology. A terminal and its AP are placed closely each other within 0.1 m.

Figure 1 shows throughput characteristics for numbers of WLANs. Numbers of terminals are fixed to 18. For example, in 2 and 6 sets of WLANs, each WLAN has 9 and 3 terminals, respectively. In the case of distance 0.05 m denoted “0 m” in the figure, the curve monotonically decreased as number of WLANs increased. As a number of active terminals including APs in whole WLANs increases, the throughput is likely to be decreased. Since very little capture effect was obtained because adjacent WLANs were too closely located to avoid interference from others, throughput is likely to be increased. In this case, capture effect was so little that could not win against effect of numbers of active terminals. Thus, throughput decreased.

On the other hand, in the case of distance 1.0 m denoted “1.0 m” in the figure, in contrast, the curve monotonically increased as a number of WLANs increased. This is because capture effect is enough to win against effect of a number of active terminals.

Note that throughput can be very small in large numbers of terminals in a WLAN or in no capture effect as in “0 m” case. Collision error frequently occurs when no or very little capture effect is obtained. The errors invoke rate adaptation control which reduces transmission rate and causes *performance anomaly*.

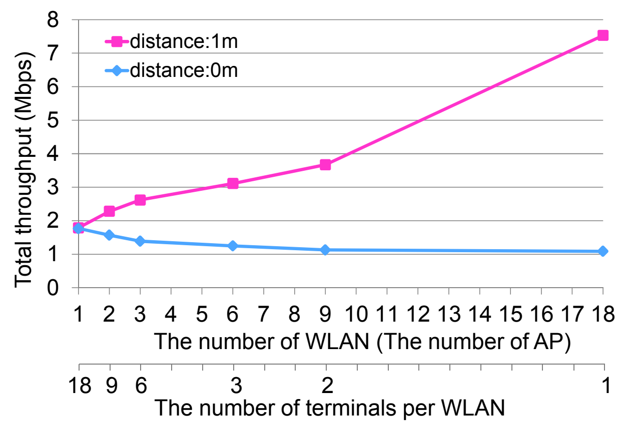

Figure 1.Total throughput for a number of WLANs

IV. Performance Anomaly

A. *Rate Adaptaion and Performance Anomaly*

Performance anomaly occurs regardless of rate adaptation behavior, but is likely to occur with rate adaptation. A sending terminal which is located far away from a receiving terminal has to use a low transmission rate. This causes performance anomaly. However, rate adaptation is a significant reason why *performance anomaly* occurs in a mobile WLAN. This is because rate adaptation control often unnecessarily decrease a transmission rate. It is only suitable to decrease a transmission rate in a case of much noise or interference. If it is difficult to differentiate frame errors by collision from by noise, a transmission rate would be decreased by collision. The decreased transmission causes total throughput degradation or *performance anomaly* of the WLAN. In addition, in densely deployed WLANs it causes *performance anomaly* over the all WLANs that use the same channel. Thus, it is important to prevent a transmission rate from decreasing.

Let us look at experimental results in which one terminal drop its transmission rate down and *performance anomaly* occurs over all the WLANs. Figure 2 indicates a relation between transmission rates and throughputs of individual terminals. In the figure, total throughput was measured in two WLANs. Each had two terminals. One of the two terminals in one WLAN was set with rate adaptation control on, but both two terminals in the other WLAN were set with rate adaptation control off and set with fixed rate of 54Mbps. At around 70 sec, the terminal with rate adaptation control on was moved away from the original position. It was moved back to the original position at 140 sec. Though the move caused transmission rate decreasing in the moved terminal, rest of the terminals remained unchanged in their transmission rate. This is because the other terminal need not to reduce their rate and were set with 54Mbps fixed rate. However, throughputs of every terminal in both WLANs were reduced. Thus, for better use of radio resources and achieving good QoS, it is very important to prevent all the terminals in densely deployed WLANs from decreasing transmission rate.

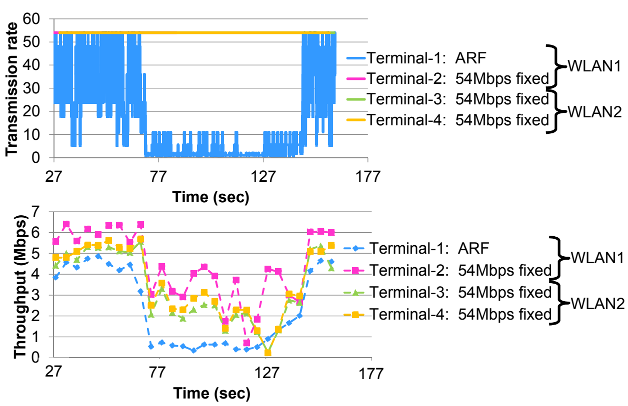

Figure 2. Throughput and transmission rate with auto rate adaptation

B. Throughput Degradation with Number of Terminals

In order to prevent unnecessary transmission rate decrease, factors affecting rate adaptation control should be known. A number of terminals in a WLAN is a key factor to cause transmission rate degradation. As a number increases, frame error rate by collision increases. In a mobile WLAN an AP and a terminal are usually very closely placed. Probability of frame errors by noise or interference is low although probability of frame errors by collision is mainly determined by a number of terminals in the WLAN.

Note that not only a number of terminals in the WLAN decides the collision rate, but also a number of terminals in other WLAN contributes to decide collision rate. Collisions between WLANs occur when Contention Windows are expired at the same time. It happens in nature as they hear their carrier each other. However, thanks to capture effect, stronger signals in a WLAN win against weaker noises from other WLANs and the collided frames are likely to be successful to be transmitted [17]. The successful rate depends on capture effect, in other words, SINR (signal to interference noise ratio). This indicates that capture effect is becoming small as a number of terminals of other WLANs is increasing. Summarizing the discussion above, probability of *performance anomaly* increases as a number of terminals in a WLAN increases, and a number of WLANs increases.

Figure 3 shows total throughput for numbers of terminals per WLAN for number of WLANs. The experiment was done with turning rate adaptation control *on* of all the terminals and the AP. All the terminals sent uplink TCP traffic to a receiving terminal via the AP. Each WLAN was located with 1.0 m distance each other in lattice topology. Each terminal and its AP are placed closely each other within 0.1 m. The throughput curve shows that two or three terminals in one WLAN are enough to give rate adaptation algorithm a specific error epoch which causes transmission rate degradation and results in poor throughput performance.

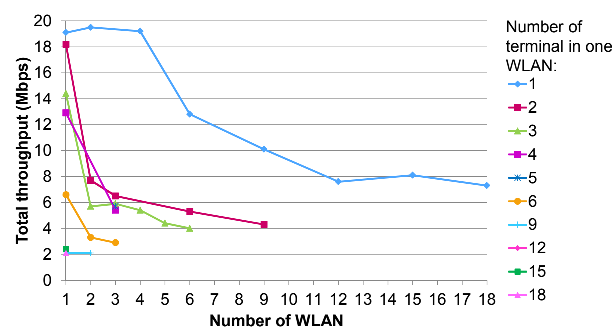

Figure 3. Total throughput and retransmission rate or frame error rate for a number of terminals in a WLAN

Figure 4 shows total throughput for numbers of WLANs, each of which consists of from 1 to 18 terminals. A number of WLANs also much affected throughput characteristics.

Figure 5 shows total throughput for numbers of WLANs with keeping total numbers of terminals fixed. It is exactly the same results and is from a different point of view of Figure 3. On each curve, total numbers of terminals are not changed but a number of WLAN and a number of terminals in each WLAN are changed. It indicates that when a fixed numbers of terminals should be accommodated in WLANs, it is better to form a few numbers of terminal and many numbers of WLANs.

Figure 4. Total throughput for a number of WLAN

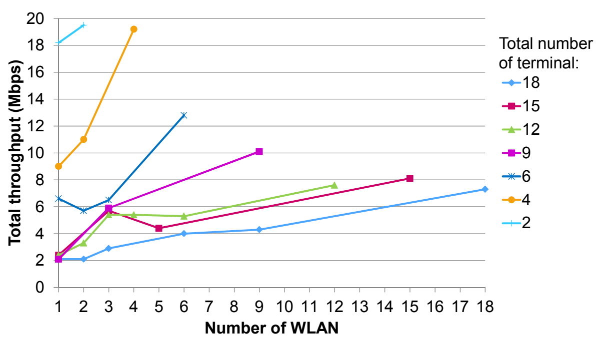

Figure 5. Total throughput of WLANs of a fixed number of terminals

V. Context Aware Multi Rate Control

A. Rate Adaptation Control

Here, it is assumed that modification of rate adaptation algorithm is not allowed but turning on/off of rate adaptation function is allowed. Because rate adaptation control which is implemented in an LSI chip is supposed to be cost-efficiently made, modification of the algorithm would be difficult but API (application program interface) could provide turn on/off rate adaptation functions. Note that turning rate adaptation control off means that the device has possibility to lose the connection in a case of lack of enough signal strength.

When an AP and terminals are very closed placed in a WLAN such as mobile WLAN or tethering devices, rate adaptation does not so effectively work. In addition, rate adaptation control causes unnecessary transmission rate degradation.

Based on these assumptions and discussions, a rate adaptation control method will be introduced in the next subsection.

B. CARC and Throughput Improvement

Context Aware multi Rate Control (CARC) is proposed for avoid unnecessary rate adaptations. In CARC, communication situations or context are categorized into two as shown in Table 1. One is called personal mode, and thither is local/public mode. In the personal mode, any rate adaptation controls are turned off and the transmission rate is fixed with the highest rate, for example, 54Mbps in 802.11g. In the local/public mode, rate adaptation control is turned on. CARC is very simple and easy to be implemented as well as effective as described in the followings.

Context may be determined as follows. When tethering or mobile AP is used, personal mode is set. Otherwise local/public mode is set. In mobile WLANs, an AP and terminals are located so close each other, and there rarely have frame errors by noise bit errors. In this case, by turning off rate adaptation control, unnecessary transmission rate adaptation can be prevented. Thus, personal mode is used. However, in the residence or public spaces, frame errors by bit errors are expected to occur because APs which is usually fixed and their associated mobile terminals are located with a certain distance. In addition, it is very difficult to estimate the optimal transmission rate because of terminal mobility. Thus, local/public mode is used.

Table 1. Modes of CARC

Mode	Rate adaptation	Signal Strength	Context
Personal	Off (Fixed rate)	Stronger signal	Mobile WLAN
Local/ public	On	Weaker signal	Public hotspot and residential or office

Recall that to turn rate adaptation control off means that the device has possibility to lose the connection in a case of lack of enough signal strength. Therefore, it is important to discuss how to switch the mode. Although optimal designs of changing mode according to the situation or context of communications are for further study, tentatively, the modes are set as follows. The mode in the terminal is switched by the received signal strength from the associated AP. If the terminal detects the signal over a specific threshold (called rate adaptation threshold), it estimates the associated AP is near and it uses personal mode. Otherwise, it uses local/public mode. On the other hand, a mobile AP in default uses personal mode. However, it may be desired to choose local/public mode in the case that the mobile AP is used in a resident, instead of broadband routers for wired Internet access. Another possibility to detect an epoch to switch the mode might be to use sensor devices which can notify if a terminal and an AP is away from a specified distance.

Through the discussion above, the advantages and disadvantages of turning rate adaptation control off should be quantitatively evaluated. First, total throughput is compared with and without CARC. In the experiments, the rate adaptation threshold is set to be small enough so as for the terminals and the AP to use personal modes. Three mobile WLANs were employed, in which mobile terminals are connected to their associated portable AP and send uplink TCP traffic from the terminals to the receiving terminal via the AP. Numbers of terminal varied to show the effect of rate adaptation control in each experiment. The three APs were located with 1.0 m each. The terminals were located within 0.1 m to the associated APs. In this distance, personal mode should be obviously used. In the following experiments, CARC was not implemented in the terminals but rate adaptation control was manually turned on in local/public mode and off in personal mode in the terminals.

In order to investigate the performance of CARC, results of two experiments with personal mode and local/public mode were compared. Figure 6 shows total throughput of the three WLANs. The three WLANs are called WLAN-1, WLAN-2 and WLAN-3 and each WLAN has one terminal at the initial settings. The figure has two curves of total throughput. One was measured in the experiment where all terminals were in personal mode and the other was where all terminals were in local/public mode. At time 30 sec. a new terminal was added to WLAN-1 and at 60 sec. the terminal was moved enough away where it could not be connected in the personal mode, i.e. at the fixed rate 54Mbps, but could be connected in local/public mode.

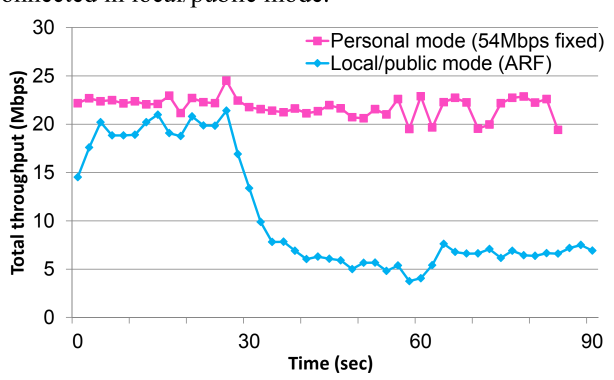

Figure 6. Total throughput of personal mode and local/public mode

At 30 sec in the Fig. 6, throughput of local/public mode was degraded because *performance anomaly* occurred. When a terminal changed its transmission rate from 54Mbps to 5.5Mbps due to frequent collisions, the total throughput of three WLANs drastically reduced from 22Mbps to 5Mbps. This was a really typical *performance anomaly*. On the other hand, that of personal mode was not degraded. The difference in the two curves at that time was approximately 3.5 times. This means that radio resources are efficiently used and QoS is much improved if all WLANs employ CARC.

After the moving, at 60 sec, in the case of personal mode, the terminal can not send any packets and its throughput becomes zero. Since the other terminal of WLAN-1 uses the bandwidth for the moving terminal, total throughput of WLANs just a little bit changes. On the other hand, in local/public mode, total throughput slightly goes up because capture effect gives a closer i.e. higher rate terminal higher priority.

C. Discussions

Because a rate adaptation algorithm is a MAC chip vender proprietary implementation as mentioned before, in order to justify the results, several kinds of smartphone and other devices were examined.

Figure 7 shows total throughput of three different WLANs and shows very similar results as in Fig. 6. Each WLAN has one terminal at the initial settings as the same as the previous experiments and the three WLAN is closely placed. To see the difference of kinds of terminals, however, rate adaptation control was turned on only in the one terminal and was turned off in the rest of the terminals and the APs. The one terminal was replaced with either Nexus S, Galaxy S2 or Mac Book Pro. While individual rate adaptation functions might show slight different quality performance as in curves in Fig.7, it might be possible to identify a typical algorithm of vendors by watching behavior of rate change. In the bottom line, CARC is useful and could be useful regardless of future rate adaptation functions.

As stated in the related works, it is desired to develop cost effective algorithm in rate adaptation to differentiate frame errors by collision from by noise. When this is difficult, CARC can be a good alternative which is very simple and easy to be implemented as well as effective to improve QoS.

VI. Conclusion

WLANs densely deployed are investigated in terms of throughput performance characteristics. In order to improve the throughput with avoiding *performance anomaly*, context aware multi rate control (CARC) is proposed. By interferences and collisions, *performance anomaly* resulting from rate adaptation forces to decrease total throughput of whole WLANs as numbers of terminals in a WLAN increases and numbers of WLANs increases. When a terminal changed its transmission rate from 54Mbps to 5.5Mbps due to frequent collisions, the total throughput of three WLANs drastically reduced from 22Mbps to 5Mbps (*performance anomaly*). To avoid the unnecessary drop of the transmission rate, CARC turns-off rate adaptation control in personal mode such as in tethering or MiFi mode, but turns-on in local/public mode such as in fixed WiFi mode for resident or public WiFi. The experiments showed that employing the CARC achieves 3.5 times improvement in the total throughput. The authors hope that this investigation open up a new usage of control parameters for mobile WLANs in order to efficiently use radio resources and to obtain higher throughput.

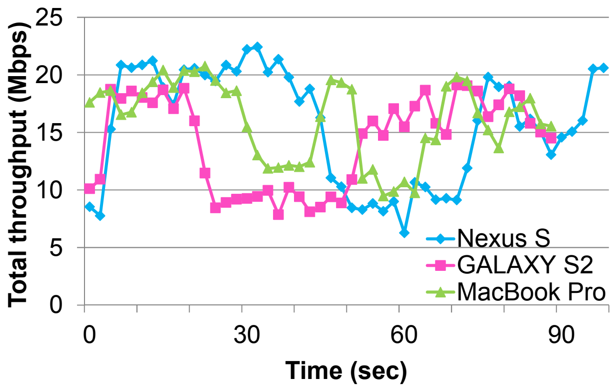

Figure 7. Rate adaptation behavior of various wireless devices

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