

The Analysis of Achieving TCP Fairness in IEEE 802.11 Infrastructure WLAN

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ABSTRACT

This paper raising the TCP fairness issues that reviewed from three aspects; per-flow, per-station, and per-rate based on the IEEE 802.11 Wireless Local Area Networks (WLANs) environment. Due to the strong drive towards wireless Internet access via mobile devices, these issues must be carefully handled in order to build improved systems. We succinctly review and categorize the TCP fairness characteristic and then outline the problems and solutions from previous works through comparative table. Finally, we considered the future direction for solving these problems. Overall this paper summarizes current state of knowledge of the WLAN TCP fairness.

Keywords

Fairness, TCP, WLAN

1.0 INTRODUCTION

Wireless Local Area Network (WLAN) has become popular due to ease of installation, and location freedom with the gaining popularity of mobile devices. Public businesses such as coffee shops or malls have begun to offer wireless access to their customers, some are even provided as a free service. Large wireless network projects are being put up in many major cities due to its convenience implementation and deployment. The number of WLAN users and devices is also increasing explosively. Besides laptops and personal digital assistants, many new mobile devices such as cellular phones, portable media players, and portable game devices tend to support Internet connectivity via WLAN hotspots. While replete with the conveniences and advantages described above, WLAN has its share of downfalls. Fairness among services provided is one of the most crucial concerns to be considered.

This paper focuses on the Transmission Control Protocol (TCP) fairness and categorized the unfairness problems into three major studies in the TCP fairness issues. Note that most of the traffic in the current Internet utilizes TCP as transport layer protocol and that most of WLANs operate in the IEEE 802.11 infrastructure mode. The prime concern for TCP is congestion that causes unfairness state among TCP connections. For assuring fairness conditions, TCP through the congestion control mechanism managed TCP flows and dealt with packet

losses efficiently. Towards the other layer, in order to handle contention for accessing wireless medium, current implementation of 802.11 (e. IEEE Computer Society LAN MAN Standard Committee, 1997) uses the Distributed Coordination Function (DCF), which provides equivalent medium access priority to all mobile stations. As we can see, WLAN fairly deal with fairness by giving similar channel access opportunity to all contending wireless devices through DCF while TCP as transport layer protocol work as congestion mechanism by handle flow and congestion control among contenders. However, the interaction between DCF and TCP itself can cause unfairness among flows, stations and rates of TCP connections that will be discussed in next section. TCP unfairness may result in significant degradation of performance forwarding to users perceiving unsatisfactory quality of service.

Remaining of this paper is organized as follows. Section 2 will give an overview of the fairness properties of TCP over WLANs. In section 3, we present the overview of the problem related to TCP fairness over 802.11 networks. In section 4, we review some related works on per-flow, per-station and per-rate problems respectively. The comparative analysis is in section 5 and the article concluded with final remarks.

2.0 TCP FAIRNESS IN WLANS

TCP as the most popular transport layer protocol surmount fairness issues by controlling the flow, error and congestion. In TCP, a sliding window (precisely three type of window involved) protocol is used to implement flow control; congestion window indicates the maximum number of packets that the sender can transmit without congesting the network, advertised window indicates to the sender the amount of data the receiver is ready to receive in the future, and transmission window means the maximum number of packets that the sender can transmit at one time without receiving any ACKs from the receiver. As stated before, a prime concern for TCP is congestion. Congestion occurs when an access point (AP) is overloaded with traffic that causes its queues to build up and eventually overflow, leading to high delays and packet losses. TCP unfairness basically cause by packet losses or dropping mechanism at the AP's queues. When any packet loss detected, besides retransmitting the loss packet, TCP also reduce its transmission rate, allowing AP queues to drain. Subsequently, it

gradually increases its transmission rate to gently probe the network's capacity and assured the fairness among TCP connection's flows.

In 802.11 WLANs standard, fairness among contending mobile stations is assured by the Media Access Control (MAC) layer through the DCF, which control and give equal access prospect channel to related stations. Fairness is one of the core problems that any MAC protocol must address. It prevents the situation that some hosts obtain most of the channel's bandwidth while others get starve (Jian & Chen, 2008). All stations compete for accessing the channel is done via the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol, which sense the channel before transmitting. If the medium is idle for a certain time (particularly equal to the distributed inter-frame space (DIFS)), the packet will be transmitted and those station then successfully access the channel. Otherwise, the station enters backoff and randomly sets its backoff counter within the range of its contention window. Each station maintains a retry counter that indicates the number of retransmission tries.

When all stations experience with similar channel conditions, CSMA/CA will provides equal transmission opportunity for all participating stations. They will achieve equivalent throughput (throughput-based fairness) when frame size used by all stations is also same. Because of varying channel circumstances (i.e., different number and direction of flows, varies application and station, different rates, etc.), IEEE 802.11 WLAN standard also support multiple data rates with dynamic rate switching capability in improving the performance.

Supposedly, if all basis mechanisms stated above work according to whatever it alleged, fairness will not be an issue. Unfortunately, interaction between the congestion control of TCP and contention control of MAC (DCF) reveal contradict results. One of the reasons is that the TCP congestion control adjusts the sending rate of a TCP flow, thus the opportunity for a wireless station to take part in the MAC-layer contention is essentially limited by the TCP congestion control (Park, Kim, Choi & Kim 2008).

3.0 PROBLEM OVERVIEW

Fairness problem in WLANs can be caused by the 802.11 TCP congestion control mechanism and MAC layer contention mechanism. The TCP congestion control mechanism with a cumulative ACK mechanism affect the behavior of a flow quite differently, depending on whether the flow is uplink or downlink. The TCP-induced asymmetry makes the service biased toward uplink flows (Park, Kim & Choi, 2006). This bias results from the asymmetric behavior of TCP flows responding to packet loss. Both TCP uplink and downlink flows react to the packet loss in different ways. When a downlink data packet is lost, a time-out occurs at the sender, or the receiver transmits duplicate ACKs to inform the sender of

packet loss. Accordingly the sender based on TCP congestion control mechanism has to reduces its congestion window size that resulting decreases of downlink throughput. However, the lost of an ACK packet for uplink does not affect its throughput much due to the cumulative ACK mechanisms of TCP. We noted this scenario as per-flow fairness problem, where each of data and ACK flow supposes having equal channel share and same action taken against packet loss situation.

The 802.11 MAC protocol purposely gave equal access opportunity to all wireless stations. However, in certainty only uplink stations and AP are participated in competing to access the channel. Thus, a single uplink station has chance with probability of one half, and each downlink station has opportunity to access the channel with probability of another half shared with the AP (Seyedzadegan & Othman, 2008). Accordingly unfairness will occur. Duly, every station shares an equal channel and opportunity of accessing those channels. This scenario denoted as per-station fairness problem.

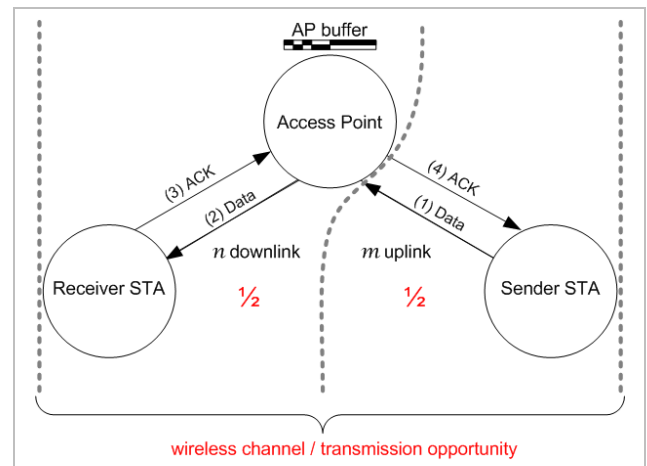


Figure 1: Schematic diagram of wireless channel shared by AP, receiver and sender station.

Figure 1 above shows an AP shares wireless channel with its mobile stations. If N stations and an AP are always contending for the access to the wireless channel, each host ends up having an approximately $1/(N+1)$ share of the total transmission opportunities over a long time interval. This result in $N/(N+1)$ of the transmission being in the uplink, while only $1/(N+1)$ of the transmissions belong to the downlink flows. The more number of sender station increases, the more serious becomes the unfairness problem.

There is another way to define fairness on a wireless channel that namely as per-rate fairness. When equal-sized frames are used and channel conditions are similar, each of uplink and downlink stations, regardless of their data rate can achieves the same amount of throughput. Today's IEEE 802.11 WLANs provide multiple data transmission rates by employing different sets of modulation and channel coding schemes. These multiple

transmission rates can be used for frame transmission in an adaptive manner, depending on the underlying channel conditions. However, the time to send a frame depends on the data rate used, and the stations with a lower rate will take longer time to transmit a frame. Hence, in multi-rate WLANs, the system capacity will be decreases because of low-rate transmission consume a lot of channel time. This unfair time allocation for stations with different transmission rates is reflected with the reduced throughput of stations with higher-rate. Since DCF (CSMA/CA) provides throughput-based fairness, the performance of the high-rate stations is bounded by the performance of the stations using lower rates. This phenomenon is referred as a performance anomaly of the 802.11 (Heusse, Rousseu, Berger-Sabbatel & Duda, 2003).

From the issues raised above, we conclude fairness problem into three categories. First category noted as per-flow fairness which is defined as equal channel share and same action taken against packet loss situation among the TCP flows. Second category is per-station fairness, defined as an equal channel share for every station by taking into account the different number and direction of flows for each station. Lastly, the third category is per-rate fairness which is defined as an equal share of wireless channel occupancy time by each station from different transmission rate. The different number of station and its flows among rates provided also taken into account.

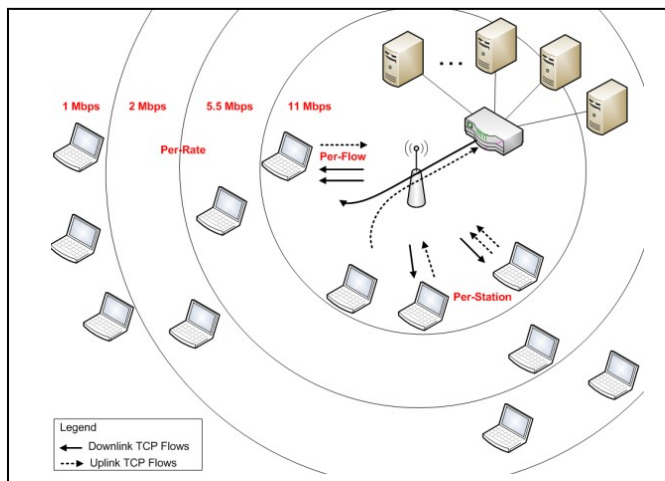


Figure 2: Network architecture shows the fairness categories

Figure 2 above shows the network architecture that illustrates the fairness categories in the IEEE 802.11b multi-rate WLAN environment. Each station can establish connection with corresponding stations in both directions (uplink and downlink) through an AP. Per-flow fairness category is showed through competition among flows within the same station. For per-station fairness category, competition is among stations that have various flows condition while per-rate fairness category is showed by different transmission rate having different station and number of flows competing on it.

4.0 REVIEW OF FAIRNESS CATEGORY

The following subsections are organized as follows. Subsection 4.1, 4.2, and 4.3 review TCP fairness previous works according to per-flow fairness, per-station fairness and per-rate fairness, respectively.

4.1 Review of Per-Flow Fairness

Fundamental issue of TCP fairness in the presence of both sender and receiver was firstly highlighted by (Pilosof, Ramjee, Shavitt & Sinha, 2003) among the TCP flows, particularly between receiver's uplink TCP ACK flow and sender's downlink TCP data flow. Hence, we categorized all research done along this characteristic as in per-flow fairness category. In this category, the TCP-induced asymmetric behavior, as TCP ACK gains more bandwidth usage than TCP data, was the main cause of unfairness. The AP buffer size indeed plays a critical role in determining the ratio between the flows (Pilosof et al., 2003). They use and manipulate the advertise receiver window field in ACK packet towards TCP sender so the window is limited to whatever value decided. Somehow, one needs to keep a counter that approximates the exact number of active TCP flow in the system. It is also very complex to implements where the AP needs to manipulate TCP header of all packets that gone through it.

Another method is by using a dual queue based scheme employed at AP; one queue for the downlink TCP data packets, and another queue for the ACK packets corresponding to the uplink TCP flows (Ha and Choi, 2006). The AP controls the service rate of each queue by selecting each queue with different probability when MAC service is ready. In order to implement this scheme, AP has to classify a packet as data packet or an ACK packet, and also has to know the number of uplink and downlink flows.

Recently, active queue management approach that implemented at the AP has proposed, which also utilizes two queues virtually; the TCP ACK queue and TCP data queue, with their length controlled by proportional integral controllers (Xia, Jin & Hamdi, 2008). As a result, data losses can be reduced since the AP's downlink buffers is no longer overwhelmed by TCP ACK packets destined to the uplink stations.

A dynamic contention window control scheme (HS Abeysekera, Matsuda and Takine, 2008) can control the minimum contention window CW_{min} of an AP according to the target packet ratio R between uplink and downlink flows. Regardless of the number of uplink flows, the optimal CW_{min} at AP is given by an explicit function of R . Thus, AP can easily compute the optimal CW_{min} to achieve fairness between uplink and downlink flows. However, this scheme may require AP to know some information about downlink flows including the number of the station (with the number of downlink flows).

4.2 Review of Per-Station Fairness

Most of the solutions proposed in per-flow fairness category cannot guarantee and provide per-station fairness when each station has a different number and direction of flows. In this sub-section, we only consider on per-station TCP fairness. In Distributed Access Time Control (DATC) scheme (Kim, Park & Choi, 2006), each station controls the rates of its TCP flows on the channel access time. There is a target access time that is calculated by dividing a sample period of time over number of active nodes in that period. When the average transmitting time of mobile stations during a sample period of time exceeds the target time, the stations should prevent access to the channel. Each period of time, target access time will be updated according to the new condition of network. Also at each period of time by using the information about capacity of channel, calculated target time, and the time of used by each station for transmission, the dropping probability is calculated. By dropping the TCP packets for certain station with related probability, the bandwidth of that station can be adjusted. DATC scheme showed that the rate for each station can be converted to the target rate in assuring that each mobile station has fair bandwidth regardless of the number and direction of TCP flows. DATC is implemented in mobile stations. This solution required computational work in each station where the rate regulator needs to run some probability calculation for dropping the packet when congestion happens at AP.

Similarly to DATC, ATC scheme (Kim, 2006) is another method that monitors the access time of each station during the sample period of time and controls the rate of transmitting for each station by dropping probability. Unlike the DATC scheme, controlling the fairness per-station is implemented at the AP centrally.

A simple solution for overcome the per-station fairness is by manipulating the TCP sender window size for ensuring that the TCP sender window size is limited to whatever value decided (Seyedzadegan et al., 2008). This method efficiently works for TCP throughput-based fairness, unfortunately not considered other TCP per-station fairness issues (i.e., time-based or temporal and proportional fairness issue). Intensive investigation have been done and been showed that current WLAN hotspot provides more services to the sender stations compared to the receiver stations, causing the sender stations to dominate the use of network bandwidth while the receiver stations starve (Park et al., 2008). They also pointed out that the unfairness originates from two asymmetries; TCP asymmetry occurring in responses to packet loss and MAC asymmetry in accessing wireless channel. They showed that TCP congestion control mechanism essentially governs the channel access attempts of IEEE 802.11 MAC. For solution, they proposed the cross-layer feedback approach in which the MAC layer at AP measures the per-station channel utilization and system-wide channel utilization to calculate the channel access cost. Sender

station uses the cost in order to assure per-station fairness and to maximize channel utilization simultaneously.

4.3 Review of Per-Rate Fairness

Since DCF provides throughput-based fairness, the performance of the high-rate stations is bounded by the performance of the stations using lower rates. This phenomenon is referred to as a performance anomaly of the 802.11. The performance anomaly of IEEE 802.11b has been analyzed using a simplified model with saturated sources, but no solution was proposed in solving the unfairness issue (Heusse et al., 2003). They proved that, if there are two different bit rates in the same environment, the saturation throughput of any station will be equal to the station with lower rate.

The main reason of poor performance of TCP in multi-rate WLANs environments is due to the fact that congestion window of higher data flow increases more rapidly, cause buffer overflows at AP and significantly influenced throughput fairness among multiple TCP flows at different data rates (Lee, Kwon, Kim & Suh, 2006). The increment rate of congestion window size is high because of round trip time is quite small. The total throughput can be increased by guaranteeing TCP temporal fairness and proposed rate-adaptive flow control scheme in which rate-proportional buffer allocation is performed at the AP.

A cross-layer scheme that exploits IP path Maximum Transmission Unit (MTU) discovery has been proposed where it adjusts message size used by different stations to insure that the time used by each station is as close (to equal to other stations) as can be achieved (Dunn, Neufeld, Sheth, Grunwald & Bennet, 2006). It needs to determine maximum message size for individual stations and then force the stations to use that maximum message size.

To overcome the performance anomaly, packet fair scheduling which provides equal channel usage time for each flow by taking into account the data rate, the packet size and the contention overhead of each flow have been suggested (Seok, Kwon & Choi, 2007). They proposed a contention aware temporally fair scheduling algorithm (CATS) that fairly allocates channel usage time rather than the variable data and packet size of mobile stations. CATS determines the scheduling order of packets as their virtual finish time. The decentralized version of CATS (D-CATS) also been proposed and it can controls the number of mobile stations that are permitted to contend for the shared wireless link.

5.0 COMPARATIVE ANALYSIS

Table 1: Comparison of reviewed schemes.

Fairness Category	Causes	Propose Solution	Findings	Comments
Per-flow	TCP data pays penalty for TCP ACK privilege	(Pilosof et al., 2003) LossLess – manipulate RCVR field in ACK packets towards TCP sender (by lowering RW)	Buffer size at BS plays a key role in observing unfairness	Very complex to implement - AP needs to manipulate TCP header of all packets
		(Ha et al., 2006) Employs two queues at AP; a queue for the downlink TCP data packets, and another queue for the uplink ACK packets	Single larger queue size induces a large queuing delay	AP has to classify a packet as data packet or ACK packet, and has to know number flows
		(Xia et al., 2008) Dual Virtual AQM - estimation algorithm of AP buffer size based on average window size	Control the number of TCP ACKs and AP channel accesses priority simultaneously	Amount of virtual and physical queue could not be arbitrary adjustable
		(HS Abeyssekera et al., 2008) Dynamically control minimum contention window size at AP into targeted packet ratio	Change fixed 802.11e CW_{min} size into dynamic control for controlling the access categories	Requires AP to know some information about downlink flows
Per-station	Each station has different number and direction of flow	(Kim et al., 2006) DATC - control the rates by using time (of station)	Mobile stations can control their rate of transmitting individually	Requires computational work in each corresponding station
		(Kim, 2006) ATC - AP monitor the access time and transmission rate of each station	Packets dropping for certain mobile station with related probability	Requires computational work in the AP
		(Seyedzadegan et al., 2008) WW - manipulate TCP sender window size (limits to whatever value decided)	Simple solution for adjusting sender window size	Implements in each of corresponding mobile station
		(Park et al., 2008) Cross-layer feedback approach - AP measures channel utilization to calculate channel access cost	TCP asymmetry responses to packet loss and MAC asymmetry in accessing wireless channel	Cover most of fairness issues
Per-rate	Each rate has different number of flow and station	(Lee et al., 2006) Rate-adaptive flow control scheme - calculates sending station feedback value	Increment rate of congestion window size high because of its' RTT is small	Basis work for per-rate fairness by allocates optimal rate for each flow
		(Dunn et al., 2006) Cross-layer scheme that exploits IP path MTU discovery	Achieve fairness by adjusting message size used by each station	Force the stations to use determine max message size
		(Seok et al., 2007) CATS – wireless packet scheduling algorithm using multi-rate wireless channel model & counting channel usage time	2 characteristics in multi-rate WLAN environments; mobility and application independence	Different works for each of flow, apply two new queue algorithm for both directions at AP

Table 1 shows the comparison of reviewed schemes. As for comparison, most of the proposed schemes are initially working on per-flow fairness where they tried to overcome the unfairness problem caused by basis interaction mechanism between TCP congestion and MAC contention. Then the issue goes to per-station fairness where the intention is given to trouncing fairness among competing stations that have different number and direction of flows. As the IEEE 802.11 provide multi-rate capability on data transmission, per-rate fairness issues raise due to the different number of station (with different number and direction of flows) competing on it. In early days, previous solutions are required to modify the existing MAC protocol and thus, are impractical to apply for current infrastructure WLANs. By the way, the schemes reviewed in this paper are not required MAC modification, but are complex to be implementing.

6.0 CONCLUSION

Through the analysis, we investigated three different notions of fairness in an infrastructure WLAN; per-flow, per-station and per-rate fairness. This paper has given an account of fairness and the reasons for the unfairness in infrastructure WLAN. The analysis (according to Table 1) has shown that most of the researchers are considering fairness for per-flow. Since the real networks are using more than one flow per-station, different direction and data transmission rate for each, future researchers should focus more on the fairness per-rate in their studies. Thus, the TCP per-rate fairness is the one of the open issues in the wireless world.

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