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Half Direct-Link Setup (H-DLS) for Fairness between External and Local TCP Connections in IEEE 802.11e Wireless LANs

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Abstract— **The IEEE 802.11e standard supports a Direct-Link Setup (DLS) mechanism optionally to improve the throughput. Using this mechanism, IEEE 802.11e stations in proximity can directly exchange frames with no intervention of an access point. However, extensive simulations reveal the severe unfairness between external and local TCP connections in the IEEE 802.11e DLS mode due to the characteristics of TCP: a window-based flow control mechanism. This paper first analyzes why a fairness problem happens between external and local TCP connections in the IEEE 802.11e DLS mode. Then, we seeks to achieve fairness between them by introducing a novel mechanism dubbed Half Direct-Link Setup Plus (H-DLS) which differentiates the paths for TCP DATA and ACK packets of local TCP connections. Simulation results reveal that H-DLS achieves the fairness between external and local TCP connections while keeping the aggregate throughput higher than the original IEEE 802.11 infrastructure.**

I. Introduction

To date, IEEE 802.11 [1] has become the de facto standard for wireless LANs due to easy installation and low cost. However, the original IEEE 802.11 protocol has no consideration for service differentiation depending on kinds of applications. Therefore, IEEE 802.11e [2] has been recently finalized to improve Quality of Service (QoS), e.g., better support of audio and video applications. In addition to QoS enhancement, IEEE 802.11e optionally adopts other functionalities such as Block Acknowledgement (BA) and Direct Link Setup (DLS) to improve throughput. For example, the BA mechanism improves channel efficiency by aggregating several acknowledgements into a single frame.

As wireless LANs become more popular, the total amount of local connections[1] generated by users in the neighborhood is also increasing. In general, even though a source and a destination STAs are in the same basic service set (BSS), the source STA is not allowed to transmit frames directly to the destination STA in the IEEE 802.11 infrastructure mode. Instead, the source STA first sends frames to its associated access point (AP), and then the AP forwards the frames to the destination STA. Thus, in the IEEE 802.11 infrastructure mode, a local connection consumes as twice wireless capacity as an external connection does. However, a source QSTA[2] with a DLS capability is allowed to transmit frames directly to another destination QSTA with a DLS capability by setting up a direct link between the source and the destination QSTAs to deliver the frames of a local connection. Therefore, the DLS protocol can increase the throughput of local connections by eliminating unnecessary relaying at an AP.

In [3-7], they defined a fairness problem between TCP connections in IEEE 802.11 wireless LANs. However, they focused on a fairness problem between only external TCP connections (e.g., uploading TCP connections, downloading TCP connections, or uploading and downloading TCP connections). To the best of our knowledge, this paper is the first contribution to study a fairness problem between external and local TCP connections in IEEE 802.11e wireless LANs. Especially, we observed that the aggregate throughput of external TCP connections is starved by local TCP connections using the IEEE 802.11e DLS protocol. Therefore, in this paper, we analyze the starvation phenomenon and then propose how to provide fairness between external and local TCP connections by alleviating the starvation of external TCP connections.

The remainder of this paper is organized as follows. In Section II, we define a fairness problem between external and local TCP connections, and analyze why the fairness problem takes place. Then, our mechanism called *Half Direct-Link Setup Plus* (H-DLS) is proposed to enhance the fairness among TCP connections in IEEE 802.11e wireless LANs in Section III. Section IV presents simulation results in terms of aggregate throughput and fairness index. Finally, we conclude our work in Section V.

II. Fairness Issues between External and Local TCP Connections

In this section, we first investigate fairness between external and local TCP connections in the original IEEE 802.11 infrastructure mode. Then, we compare the fairness in the IEEE 802.11 infrastructure mode with the one in the IEEE 802.11e DLS mode, and analyze why they show different levels of

[1] A *local connection* means that both a source and a destination STAs are in the same BSS, while an *external connection* means that either a source or destination STA is out of the BSS.

[2] A station with IEEE 802.11e is called a QoS station, denoted by QSTA.

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fairness. For this purpose, we use a fairness index in [9], which is a normalized measure that ranges between zero and one. The fairness index indicates how fairly resources are allocated among the given contenders. In all simulations, all (Q)STAs and (Q)AP are close enough to use 11Mbps as a data rate between them, and the buffer size of the (Q)AP is set to a value large enough to eliminate its effect on fairness. The network has $2n$ external and n local TCP connections. More precisely, $2n$ external TCP connections consist of n uploading and n downloading TCP connections, varying the number n.

A. IEEE 802.11 Infrastructure Mode

Fig. 1 shows the performance of each type of TCP connections in the IEEE 802.11 infrastructure mode when external and local TCP connections coexist. In the IEEE 802.11 infrastructure mode, an external (uploading or downloading) TCP connection needs only a single transmission in the wireless part for a packet, while a local TCP connection requires two transmissions for a packet due to the relay of an AP. Therefore, the throughput of uploading (or downloading) TCP connections is roughly twice larger than that of local TCP connections as shown in Fig. 1(a). It is noted that the throughput of uploading (or downloading) TCP connections is kept independently of the number of TCP connections, and the aggregate throughput of TCP connections is also kept around 2.8 Mbps.

We can also see fairness among all types of TCP connections in Fig. 1(b). There is no fairness problem among uploading (or downloading) TCP connections. A fairness problem between uploading and downloading TCP connections does not also arise due to a large buffer size on an AP. On the other hand, fairness among local TCP connections gets a little worse as the number of TCP connections increases. Fairness between external and local TCP connections is worse than the one among local TCP connections but even in the worst case the fairness index is kept over about 0.8.

B. IEEE 802.11e Direct Link Setup Mode

If the IEEE 802.11e DLS mode, QSTAs with a local TCP connection also requires only a single transmission for a packet, so it is expected that the throughputs of uploading, downloading and local TCP connections are similar. As shown in Fig. 2(a), however, there is a large difference between external and local TCP connections. As the number of TCP connections increases, the throughput of external (uploading or downloading) TCP connections continues to get worse, and that of local TCP connections is getting higher. This is due to the characteristics of TCP, which will be explained in the next subsection. The aggregate throughput of TCP connections is about 3.3 Mbps, which is higher than 2.8 Mbps in the IEEE 802.11 infrastructure mode. This is because the DLS mechanism eliminates unnecessary transmission via an QAP, and moreover, the characteristics of TCP boosts up the improvement.

As shown in Fig. 2(b), severe unfairness arises in the IEEE 802.11e DLS mode unlike the IEEE 802.11 infrastructure

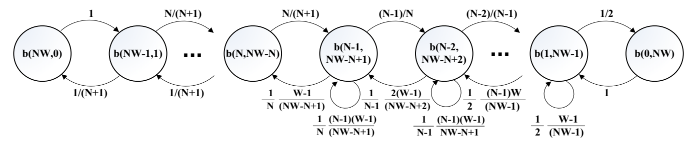

Fig. 3. An n-state Marckov chain for uploading TCP connections in IEEE 802.11 wireless LANs.

mode. Although fairness among local TCP connections is similar to the trend in Fig. 1(b), other kinds of fairness shows large differences. A fairness problem between external and local TCP connections inevitably takes place because local TCP connections consume far more bandwidth than external TCP connections in the IEEE 802.11e DLS mode. In the worst case, the fairness index goes down below 0.5. It is because the greedy behaviors of local TCP connections have a negative effect on external TCP connections. In addition, fairness among uploading (or downloading) TCP connections, and between uploading and downloading TCP connections are also damaged.

C. TCP connections in IEEE 802.11 wireless LANs

In order to understand the starvation of external TCP connections in the IEEE 802.11e DLS mode, we need to know that TCP connections in IEEE 802.11 wireless LANs have little to do with network congestion. According to [8] that analyzes the saturation throughput of the IEEE 802.11 DCF, as the number of active STAs[3] increases, the saturation throughput of IEEE 802.11 wireless LANs decreases. However, in [7], Choi et al. presented different experimental results about the performance of TCP connections in IEEE 802.11 wireless LANs. The aggregated throughput of TCP connections is stable even though the number of STAs increases. The reason is that the number of active STAs is nearly the same independently of the number of STAs with a TCP connection. Since TCP adopts a window-based flow control mechanism, a TCP sender does not have any TCP DATA packet to send until it receives TCP ACK packets for transmitted TCP DATA packets. In this situation, the number of active STAs is much smaller than the number of STAs.

To simplify an analysis of this window-based flow control mechanism of TCP in IEEE 802.11 wireless LANs, we assume that all STAs and an AP get a chance to transmit a frame in a round-robin manner due to the fairness of the IEEE 802.11 DCF. Fig. 3 depicts a simple n-state Markov chain that models uploading TCP connections in the IEEE 802.11 infrastructure mode. N STAs are trying to upload TCP DATA packets to N fixed hosts via an AP. We devote the state of the network as $b(L1,\ L2)$, where $L1$ is the sum of the lengths of the queues at all STAs and $L2$ is the length of the queue at the AP. After a STA has transmitted W TCP packets, it cannot contend to transmit another TCP packet until it receives a TCP ACK

[3]A STA can be classified into an *active* or *inactive* one. An active STA is defined as a STA having at least one frame to send and participating in the wireless channel contention, while an inactive one does not try to send any frame.

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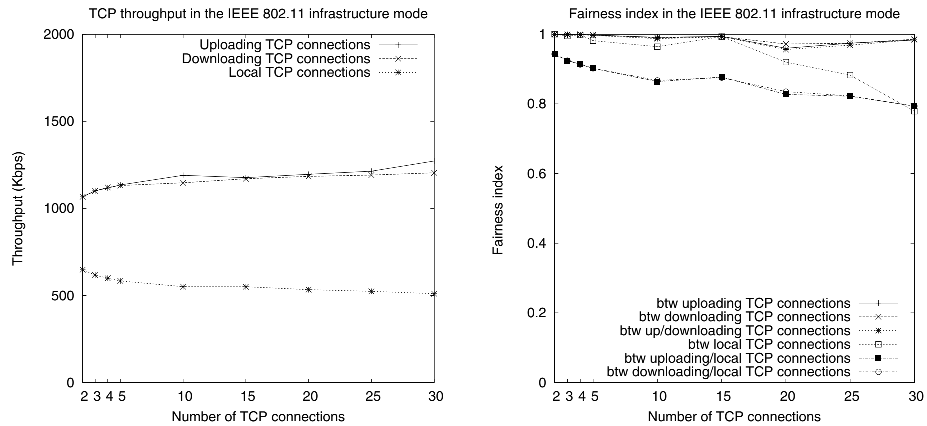
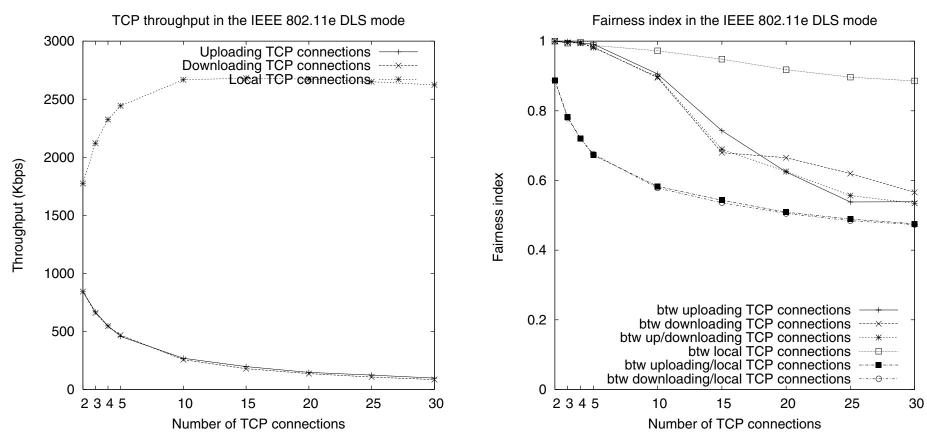


(a) Throughput (b) Fairness index

Fig. 1. TCP connections in the IEEE 802.11 infrastructure mode.



(a) Throughput (b) Fairness index

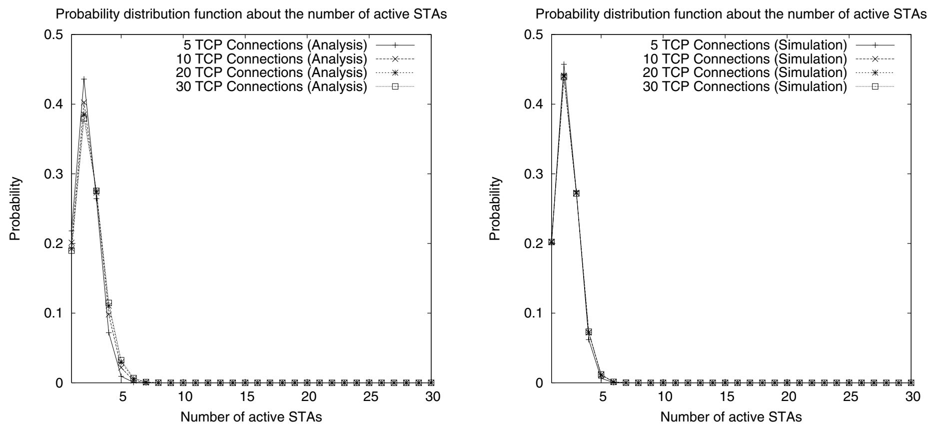
Fig. 2. TCP connections in the IEEE 802.11e DLS mode.

packet from the AP. By running MATLAB with this model until it reaches a steady state, we determined the probability density function of the number of active STAs participating in the wireless channel contention, and these results are plotted in Fig. 4(a).

This graph shows that the number of active STAs is mostly less than five regardless of the number of STAs that are trying to upload TCP DATA packets, so the network is never saturated. These analytic results explain why the number of STAs does not affect the throughput of each type of TCP connections in the IEEE 802.11 infrastructure mode. However, in the IEEE 802.11e DLS mode, a TCP sender and a TCP receiver exchange TCP DATA and TCP ACK packets directly, so both of them always have at least a frame that contains a TCP DATA or TCP ACK packet. Therefore, the number of active STAs is almost as the same as the number of STAs with a local TCP connection, so that the network gets quickly saturated as the number of STAs increases. Our empirical study using an NS-2 simulator [11] verifies this analysis, as shown in Fig. 4(b).

D. Performance Anomaly in Multi-Rate Wireless LANs

A temporal fairness problem takes place in multi-rate wireless LANs. Suppose that there are some STAs which are distant from its associated AP but close enough to use 11Mbps between themselves, and others which are close to the AP. These network topology is probable enough in the group mobility scenarios. If the former and the latter have local and external connections, respectively, in the IEEE 802.11 infrastructure mode, this configuration causes a *performance anomaly* problem reported in [10]. The aggregate throughput of external connections with a high transmission rate, e.g., 11Mbps, is degraded to the lower aggregate throughput of local connections tuned to a low transmission rate, e.g., 1Mbps, thus the aggregate throughput of all connections is also degraded as shown in Fig. 7. However, if DLS is used, there is no performance anomaly problem because a local connection requires only a transmission on a direct-link at 11Mbps instead of two transmissions on a path via the QAP at 1Mbps to send a frame. Therefore, IEEE 802.11e DLS can also achieve the higher aggregate throughput in multi-rate IEEE 802.11e



(a) Analysis (b) Simulation

Fig. 4. Ratio of competing active STAs.

wireless LANs.

III. Half Direct-Link Setup: H-DLS

In this section, we propose a simple mechanism dubbed Half Direct-Link Setup (H-DLS) to alleviate unfairness between external and local TCP connections while keeping the aggregate throughput improved by DLS as high as possible. The basic idea behind H-DLS is to eliminate the operational differences between external and local TCP connections.

A. H-DLS Operation

As shown in Section II-B, there is a large throughput difference between external and local TCP connections in the IEEE 802.11e DLS mode. This phenomenon stems from the characteristics of TCP: a window-based flow control mechanism. In other words, both source or destination QSTAs in local TCP connections are too aggressive to make the network quickly saturated as explained in Section II-C. Therefore, a number of external TCP connections occupy only a small fraction of network capacity, compared to greedy local TCP connections. To relieve the unfairness between external and local TCP connections, we propose a novel mechanism called Half Direct-Link Setup Mechanism (H-DLS).

H-DLS differentiates the paths for TCP DATA and TCP ACK packets. A QSTA that wishes to initiate a local TCP connection creates a uni-directional direct-link instead of a bi-directional direct-link. Besides the direction of a direct-link, the detailed procedures of H-DLS are the same as the ones of IEEE 802.11e DLS. If it is successfully completed, the DLS initiating QSTA is allowed to transmit frames to the DLS recipient QSTA by using this half direct-link. However, any transmission in the reverse direction is not permitted. Thus, a frame that contains a TCP DATA packet in the forward path is transmitted directly to its destination QSTA but another frame that contains a TCP ACK packet in the reverse path has to go through a QAP. Fig. 5 shows operation differences between external and local TCP connections in H-DLS.

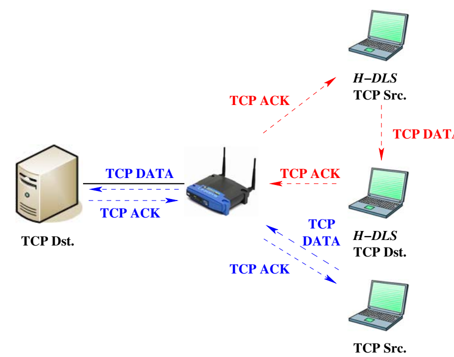


Fig. 5. The operation form of H-DLS.

By allowing only a DLS initiating QSTA to send TCP DATA packets of local TCP connections over a direct-link, TCP ACK packets from the a DLS recipient QSTA are sent to the DLS initiating QSTA via a QAP. In this case, a TCP sender does not have TCP DATA packets to send at all the time. The next TCP DATA packet is available only if the TCP ACK packet corresponding to the previous TCP DATA packet are received like those of external TCP connections. In other words, a QAP treats TCP ACK packets of all TCP connections at the same way, so that the greedy behaviors of local TCP connections is suppressed because the sending rate of TCP is controlled by the rate that TCP ACK packets are received by a TCP sender. Accordingly, it prevents local TCP connections from saturating the network, which in turn results that the throughput loss of external TCP connections damaged by local TCP connections is mitigated. However, it is expected that local TCP connections still occupy slightly more bandwidth because the shorter transmission time of TCP DATA packets results in a shorter round trip time (RTT) of the TCP connection.

In multi-rate IEEE 802.11e wireless LANs, H-DLS can also mitigate the performance anomaly in such a scenario as depicted in Section IV-B. If QSTA1 transmits frames including TCP DATA packets to QSTA2 at 11Mbps in the H-DLS mode, the channel occupancy time of the local TCP connection is shorter than that of a longer path via the AP at 1Mbps in the IEEE 802.11 infrastructure mode. Therefore, more fair channel occupancy time is given to an external TCP connection between QSTA3 and QSTA4. Although QSTA2 transmits frames including TCP ACK packets to QSTA1 at 1Mbps in the H-DLS mode, the frames have little to do with the channel occupancy time due to a small frame size. Moreover, H-DLS also guarantees fairness between external and local TCP connections because it still handles TCP ACK packets with no discrimination, which has a significant effect on the performance of TCP connections.

IV. Performance Evaluation

Using an NS-2 simulator, we conducted extensive simulations to evaluate our proposed proposal, H-DLS, varying the number n of each type of TCP connections. Two performance metrics, the aggregate throughput and fairness index, were measured and analyzed for external and local TCP connections. The network tested in these simulations consists of an QAP, $4n$ QSTAs, and $2n$ fixed hosts. n QSTAs upload TCP DATA packets to n fixed hosts via the QAP while other n QSTAs download TCP DATA packets from the rest of fixed hosts via the QAP. In addition, n QSTAs directly send TCP DATA packets to other n QSTAs on their direct links.

A. Scenario A

In Scenario A, all QSTAs and QAP are close enough to use 11Mbps as a data rate between them. Fig. 6(a) shows the throughput of each type of TCP connections in the H-DLS mode. The throughput of uploading (or downloading) TCP connections is improved to about 1000Kbps similar to the one in the IEEE 802.11 infrastructure mode, which is about 100Kbps in the IEEE 802.11e DLS mode. In terms of the aggregate throughput of all types of TCP connections, there is also a throughput gain, compared to the IEEE 802.11 infrastructure mode. This is because the throughput of local TCP connections is still improved while doing no harm to external TCP connections. In addition, although the throughput of local TCP connections is slightly higher than that of external TCP connections, it is sustained as a level similar to that of external TCP connections. This is because the H-DLS mode does not increase the number of active QSTAs by controlling the rate that TCK ACK packets are received.

Fig. 6(b) shows the fairness index of every pair of TCP connection types in the H-DLS mode. The unfairness between TCP connections is removed because H-DLS handles TCP ACK packets of local TCP connections like external TCP connections, which has a significant effect on the performance of TCP connections. Moreover, the fairness between each type of TCP connections is guaranteed despite a large number of QSTAs. This is also because the number of active QSTAs is almost five regardless of the number of QSTAs that are trying to upload TCP DATA packets as mentioned before.

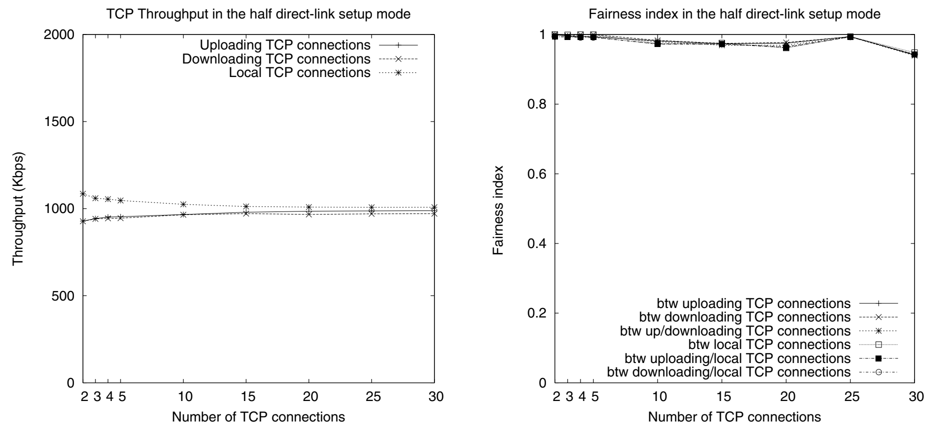
B. Scenario B

To show that H-DLS relieves the performance anomaly phenomenon, in Scenario B, n QSTAs with a local TCP connection are located distantly from its associated QAP but close enough to use 11Mbps between themselves, and others are the same as Section IV-A. Fig. 7(a) shows the aggregate throughput of the IEEE 802.11 infrastructure mode, the IEEE 802.11e DLS mode, and the H-DLS mode. In the IEEE 802.11 infrastructure mode, QSTAs with a local TCP connection are connected to the QAP with a data rate of 1Mbps so that they reduce the channel holding time of QSTAs with a external TCP connection connected to the QAP with a data rate of 11Mbps. Accordingly, the aggregate throughput of all TCP connections are far degraded, compared to the scenario that all QSTAs are connected to the QAP with a data rate of 11Mbps. However, in the case of the IEEE 802.11e DLS mode, QSTAs with a local TCP connection exchange TCP DATA and ACK packets with a data rate of 11Mbps needlessly to pass through the QAP, thereby there is no performance anomaly. In the H-DLS mode, QSTAs with a local TCP connection directly transmit TCP DATA packets with a data rate of 11Mbps while they transmit TCP ACK packets via the QAP. The transmission time of a TCP ACK packet is short due the small packet size, thus the transmission of a TCP ACK packet does not have a large effect on the channel holding time. Therefore, the aggregate throughput is considerably improved, compared to the one in the IEEE 802.11 infrastructure. Moreover, the fairness between external and local TCP connections is still guaranteed because H-DLS deals with TCP ACK packets of all types of TCP connections at the same way.

In case of the IEEE 802.11e DLS mode, as the number of STAs increases, the aggregate throughput of TCP connections decreases as analyzed in [8]. This is because the number of active STAs is in proportion to that of STAs as explained in Section II-C. In the IEEE 802.11 infrastructure mode and the H-DLS mode, the aggregate throughput of TCP connections is nearly kept independently of the number of STAs. This is because, in these cases, the number of active QSTAs is at most around 5 despite a large number of STAs. This situation is more clear in Fig. 7(b), which shows the number of frame collisions as the number of STAs increases. In the IEEE 802.11e DLS mode, more active STAs contends for the wireless channel as the number of STAs increases, so that the number of frame collisions also increases. Local TCP connections in the H-DLS are more aggressive than in the IEEE 802.11 infrastructure mode, so the average number of frame collisions is slightly higher. However, the number of frame collisions is sustained almost constantly both in the IEEE 802.11 infrastructure mode and the H-DLS mode because the number of active STAs is always around 5.

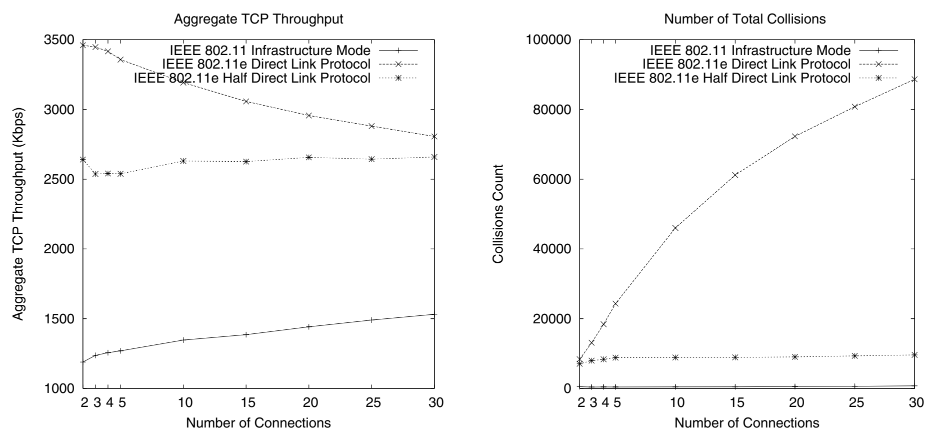
V. Conclusion

In this paper, we first pointed out the unfairness problem between external and local TCP connections in the IEEE 802.11e DLS mode. To investigate why such a fairness problem happens, we designed and analyzed a simple model on



(a) TCP Throughput (b) Fairness Index

Fig. 6. Performance of H-DLS.



(a) Aggregate throughput (b) Collision count

Fig. 7. Performance of H-DLS on performance anomaly scenario.

TCP connections in IEEE 802.11 wireless LANs. Then, we proposed Half Direct-Link Setup (H-DLS), which provides the nearly fair share of bandwidth to each TCP connection regardless of an external or local one. The central idea of H-DLS is to differentiate the paths for TCP DATA and ACK packets of local TCP connections. In detail, it seeks to achieve fairness between external and local TCP connections by dealing with all TCP ACK packets at the same way. Simulation results reveal that H-DLS achieves the fairness between external and local TCP connections while keeping the aggregate throughput higher than the original IEEE 802.11 infrastructure. Furthermore, another simulation verifies that the performance anomaly is eliminated in multi-rate IEEE 802.11e wireless LANs if H-DLS is used.

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