Fairness and Delay in MU-MIMO WLANs

Jelena Mirkovic
ComNets, Faculty 6, RWTH Aachen University, Aachen, Germany
Email: jem@comnets.rwth-aachen.de

***Abstract*—In this paper, single-user (SU) and multi-user (MU) transmission approaches in Multiple Input-Multiple Output (MIMO) Wireless Local Area Networks (WLANs) are compared. The impact of the transmission strategy on both short-term and long-term fairness and frame delay distribution is studied.**

This work is focused on the previously presented Single-User - Distributed Coordination Function (SU-DCF) and Multi-User - Distributed Coordination Function (MU-DCF), both based on the IEEE 802.11 Distributed Coordination Function (DCF). A comparative performance analysis is given, and despite the increased system complexity, it is argued in favor of MU systems.

I. Introduction

Providing fairness is a common problem, occuring in both wireless and wired networks. It has a strong impact on other network performance metrics, particularly delay, which determines the QoS for applications such as multimedia streaming and Internet gaming. *Long-* and *short-term fairness* can be differentiated, depending on the observed time periods.

In this work the scheduler of an Access Point (AP) in an MU-DCF [1] network is analysed. The provision of fairness to multiple flows with possibly different destinations when using SU and MU transmit approaches is investigated. In contrast to IEEE 802.11n networks [2], frames addressed to multiple stations can be simultaneously transmitted in MU-DCF. The performance of SU and MU approaches are compared in a hotspot scenario, showing the performance gain of MU approach, justifying increased system complexity.

II. SU-DCF and MU-DCF Description

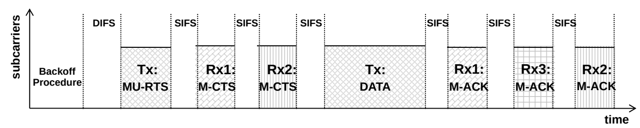
Both SU- and MU-DCF enhance the IEEE 802.11 DCF [3] with MIMO capability. The essential features of MU-DCF are:

- MU-MIMO transmission in IEEE 802.11 fashion.
- Support for fast link adaptation.
- MU-DCF is scalable, and provides backward compatibility, coexistence and interoperability to stations with different number of antennas.

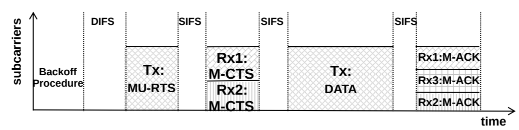
In order to reduce the signaling overhead, multiple M-CTS and M-ACK frames can be transmitted using OFDMA, instead of TDMA, as illustrated in Fig. 1(a) and 1(b). SU-DCF is a special case of MU-DCF, under the restriction that MIMO frames consist only of data frames with the same destination.

III. Comparison of SU and MU Approach

1) Saturation Throughput Evaluation: The maximum theoretically achievable throughput for DCF - single antenna system, and SU- and MU-DCF, both with TDMA and OFDMA are given in Table I (assuming one transmitting station, 802.11a PHY (54 / 36 Mb/s for data/control frames), 1024 byte frames, and 4 transmit and receive antennas). In SU-DCF, the saturation throughput is four times higher than in DCF, since four spatial channels are used. The high overhead in TDMA based MU-DCF significantly reduces its saturation throughput, while this effect is mitigated using OFDMA. These capacities do *not* depend on the number of connections.



(a) TDMA is used for transmitting the control packets



(b) OFDMA is used for transmitting the control packets

Fig. 1. Frame exchange during a MU-MIMO transmission

In this analysis, it has been assumed that the Packet Error Rate (PER) is zero. When packet errors are present, and if the channel knowledge is present at the transmitter, MU-DCF will have better performance since MU diversity will be exploited.

TABLE I
System Capacities

	Four-way handshake	Two-way handshake
DCF	20.2 Mb/s	25.5 Mb/s
SU-DCF	80.8 Mb/s	101.9 Mb/s
MU-DCF, TDMA	50.5 Mb/s	75.6 Mb/s
MU-DCF, OFDMA	75.6 Mb/s	98.3 Mb/s

2) Fairness Evaluation: As a metric, the fairness index proposed in [4] is used: $f\left(t_1, t_2\right) = \frac{\left(\sum\limits_{i=1}^{m} x_i\right)^2}{m \sum\limits_{i=1}^{m} x_i^2}$, where (t_1, t_2) is the observed interval, m is the number of contending stations, and x_i refers to number of resources used by station i within the time interval. The index takes values from the interval $[1/m, 1]$, where 1 represents maximum fairness.

In Fig. 2 analitically calculated evolution of the fairness index over time is plotted, provided by an AP with 10, 50 and 100 downlink connections with constant bit-rate. The fairness index in both SU-DCF and MU-DCF asymptotically approaches 1. However, in MU-DCF it converges much faster, indicating higher ability to provide short-term fairness. Under bursty traffic modeled by Poisson load sources, the convergence speed reduces for both approaches (Fig. 3).

3) Queue Delay Evaluation: Queue delay is the time a frame spends in the data queue until the start of the first transmission attempt. Two kinds of simulations have been performed, both on a typical hotspot scenario, with an AP and a number of downlink connections. In all the simulations, the total offered load remains below the network saturation throughput to avoid infinite queue growth. In the first set of simulations, the offered load *per connection* is fixed to 1 Mb/s, the number of connections is varied from 1 to 46. In Fig. 4, the 50^{th}, 75^{th} and 95^{th} percentiles of queue delay vs. number of stations are presented. The queue delay in SU-DCF is the highest and does not depend on the number of stations. In contrast to SU-DCF, MU-DCF starts a transmission as soon as four frames are in the queue, independently of their destination. Therefore the mean queue delay reduces, and its variance is decreased with the growing number of stations.

In the second set of simulations, the *total* offered load is fixed to 46 Mb/s, each connection contributes to it with the same fraction, and the number of connections is varied. In this case again MU-DCF outperforms SU-DCF, as shown in Fig. 5. Since the frame destination is not relevant for creating a MIMO frame in MU-DCF, the queue delay does not depend on the number of stations. On the other hand, the queue delay with SU-DCF increases linearly, and its variance increases.

IV. Conclusion

In this paper, a performance comparison of SU- and MU-DCF has been presented, with special attention on fairness, and its impact on the queue delay distribution. It has been shown that MU-DCF has higher potential to provide short-term fairness than SU-DCF. Simulation results have shown that MU-DCF benefits from multiple connections, even when the offered load is increasing. Furthermore, it has been shown how SU-DCF suffers from the multiple connections under constant load. On the other hand, when the number of connections grows, the performance of MU-DCF does not degrade. It is also worth noting that these results are independent of the medium access strategy.

Future work will focus on evaluation of SU and MU approaches for the application specific traffic characteristics, such as VoIP or multimedia streaming, saturation limits in mesh architectures and MIMO link adaptation strategies.

Acknowledgment

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References

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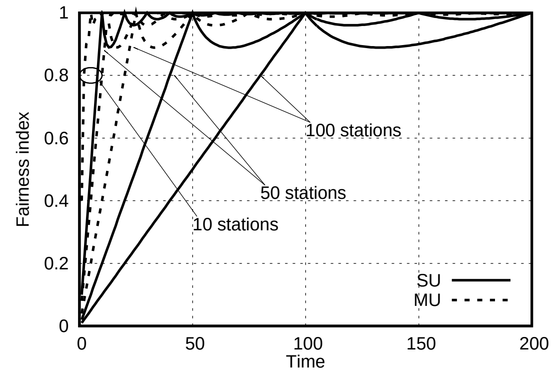

Fig. 2. Fairness index under constant bit-rate

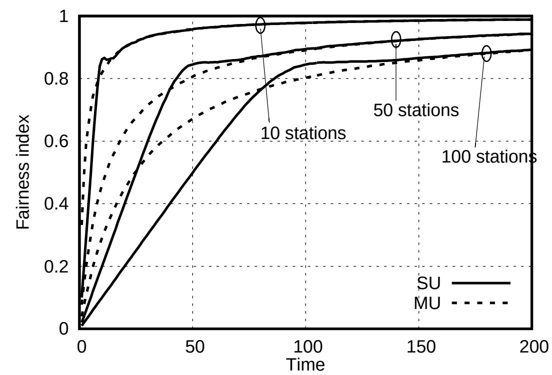

Fig. 3. Fairness index under Poisson traffic

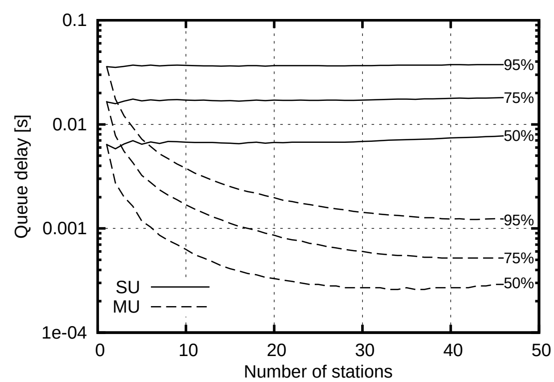

Fig. 4. Delay percentiles for the hotspot scenario: fixed load per station (1 Mb/s), varying the number of stations from 1 to 46

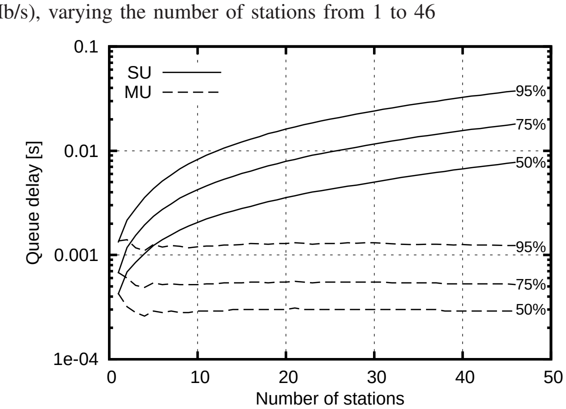

Fig. 5. Delay percentiles for the hotspot scenario: fixed total offered load (46 Mb/s), varying the number of stations from 1 to 46