# On the Importance of Loss Differentiation for Link Adaptation in Wireless LANs


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***Abstract*—In current wireless LANs multiple kinds of losses occur (i.e., channel errors, collisions, interference). In this paper we examine the extent to which loss differentiation based physical layer transmission bit–rate and contention window adaptation aids in improving network performance. We show that loss differentiation can have a positive impact on performance, especially in low contention scenarios. Crucially, the same performance can also be achieved even without the use of loss differentiation as long as the appropriate rate and contention window adaptation mechanisms are used. Our study on the impact of loss differentiation led us to develop *Themis*, a novel bit–rate and contention window adaptation scheme that does not rely on loss differentiation. *Themis* considerably improves performance over both the standard 802.11a/b/g and SampleRate in terms of throughput and fairness by reducing hidden nodes.**


## I. Introduction

Optimizing the performance of Wireless Local Area Networks (WLANs) has been a popular research topic. *Link adaptation* is key to high performance WLANs. It refers to adapting one or more link/MAC and physical (PHY) layer parameters to optimize a desired criterion such as throughput or fairness. Some examples of such link/MAC parameters are contention window and frame length, and some PHY parameters are the transmission bit-rate, transmission power and carrier sense threshold.

Link adaptation is affected by different kinds of frame losses that could occur, namely channel errors, collisions and interference (hidden terminal) losses. Previous works (e.g., [1]) claim that link adaptation mechanisms should rely on *loss differentiation* in order to effectively adapt the link every time a certain type of loss happens. Intuitively, since inappropriate responses can adversely impact achieved performance (e.g., in terms of throughput), the various causes of losses should be considered separately when designing a link adaptation scheme.

Our primary goal in this paper is to understand the potential benefit from loss differentiation on link adaptation, focusing on the two well studied parameters — PHY layer transmission bit–rate and MAC layer contention window. Assuming we have access to a perfect loss differentiator, we try to identify intuitively optimal parameter adaptation strategies for different kinds of losses (channel errors, collisions and interference) and quantify the resulting throughput gain under different network conditions. We find that loss differentiation has a positive impact on performance, especially in low contention WLAN scenarios.

*This work was done while the author was at the University of Edinburgh.

Loss differentiation, however, is a hard problem to solve since 802.11 only gives binary feedback (success/failure of a transmission). Therefore, we explore the possibility of doing away with loss differentiation while designing an effective link adaptation scheme for WLANs. We show that it is indeed possible by synthesizing a novel link adaptation scheme called *Themis* based on the insights from our study in the first part of the paper on assessing potential gains from loss differentiation. *Themis* does bit-rate and contention window adaptation without relying on loss differentiation. *Themis* uses a sampling technique for rate selection. It selects the rate to sample based on RSSI in low contention cases, whereas it randomly selects a rate to sample in high contention cases. In both cases, the rate used for data transmission is selected based on a statistical table created and updated by this sampling technique. Simulation results show that *Themis* can considerably improve performance, in terms of throughput and fairness, compared to both the standard 802.11a/b/g and SampleRate by eliminating hidden nodes.

The remainder of this paper is organized as follows. In Section II, we discuss related work. Benefits from loss differentiation is studied in Section III. The proposed link adaptation mechanism, *Themis*, is presented and evaluated in Sections IV and V, respectively. Section VI concludes the paper.

## II. Related Work

Previous work has shown that there are multiple types of losses (channel errors, collisions, interference) [2], [3] and that for each loss type, different actions for link adaptation are more efficient (e.g., [1], [4]). Authors of [1] claim that link adaptation mechanisms should rely on *loss differentiation*, since inappropriate responses can adversely impact achieved performance (e.g., in terms of throughput). Therefore, the various causes of losses should be considered separately when designing a link adaptation scheme. In [4], authors identify the most suitable set of parameters that should be adapted for each type of loss.

The majority of prior work on link adaptation in 802.11 networks has focused on adapting a specific parameter, usually the transmission bit-rate at the PHY layer (e.g., [5], [6], [7], [8], [9]) and contention window at the MAC layer (e.g., [10], [11], [12], [13]). Concerning loss differentiation, most commonly, the transmission bit–rate is adapted on encountering a channel error, whereas the contention window is adapted in the event of a collision [14], [15], [16], [17].

Despite the fact that many works have focused on link adaptation with loss differentiation (e.g., [6], [7], [16], [18], [19]), we observe that none of them consider all three different kinds of frame losses seen at the MAC layer, namely channel errors, collisions and interference (due to hidden terminals); they tend to focus on only two of the three.

In contrast to the aforementioned body of previous work, our work is motivated by the fact that loss differentiation is a complex problem to solve at runtime as also shown by some previous studies such as [4]. So we explore the possibility of designing an effective link adaptation scheme that does not rely on loss differentiation. Our approach towards this end is to first study the potential benefit from having loss differentiation capability and using insights from that study to develop a scheme that offers the same benefit but without loss differentiation.

## III. Loss Differentiation Benefits

### A. Methodology

Our goal in this section is to examine the potential gain from using loss differentiation for link adaptation in 802.11 WLANs via simulation.

We consider the common infrastructure WLAN scenario seen in home, office and hotspot environments. We study WLAN performance focusing on throughput as the main metric. We also briefly consider the fairness metric.

We also consider an ideal loss differentiator. On the receiver side, a loss is marked as a "Channel Error" if it is caused due to a weak signal (i.e., low SNR). Otherwise, there are two possibilities. We mark a loss as due to "Collision" (synchronous interference) if it has occurred while the preamble was being received. If the preamble is correctly received but the signal is not correctly decoded then we mark the error as an "Interference" (asynchronous interference) loss instead [2], [3].

In our study, we consider various link adaptation schemes some of which are assumed to have access to the aforementioned loss differentiator at the sender side. The loss differentiator uses the received signal strength indicator (RSSI) for estimating the current channel quality and inferring the cause of loss. In one of our schemes called the ORACLE, instantaneous receiver-side RSSI is assumed to be available at the sender. In other loss differentiation based schemes, RSSI is obtained at the sender from the receiver via the latest ACK frame. This is more realistic, but such RSSI information could be stale in the event of prolonged transmission inactivity or successive transmission failures.

We focus on two common parameters — PHY layer transmission bit-rate and MAC layer contention window. From the literature, intuitive actions for adapting these two parameters would be to only decrease the bit-rate (henceforth, rate) in case of channel error and only adjust the contention window if loss is not due to a channel error.

We consider the following schemes for rate adaptation. Of these schemes, Loss Aware Rate Adaptation (LARA) algorithm relies on (ideal) loss differentiation.

- *Static Rate* uses the best rate in terms of throughput depending on the distance between the access point (AP) and client, using a distance-dependent path loss model with no fading.
- *SampleRate [9]*
- *LARA (Algorithm 1)* implements the intuitive action of decreasing the rate only in case of channel error and relies on RSSI obtained via most recent ACK from receiver.
- *ORACLE* always chooses the optimal rate based on the assumed knowledge of current receiver-side channel at the sender side.

**Algorithm 1** Loss Aware Rate Adaptation (LARA) Algorithm

**if** $ChannelError$ **then**
  $rate = currRate--$
**else if** $Collision || Interference$ **then**
  $rate = currRate$
**else if** $Frame\ transmission\ is\ successful$ **then**
  $rate = highestRateBasedOnRSSI$
**end if**

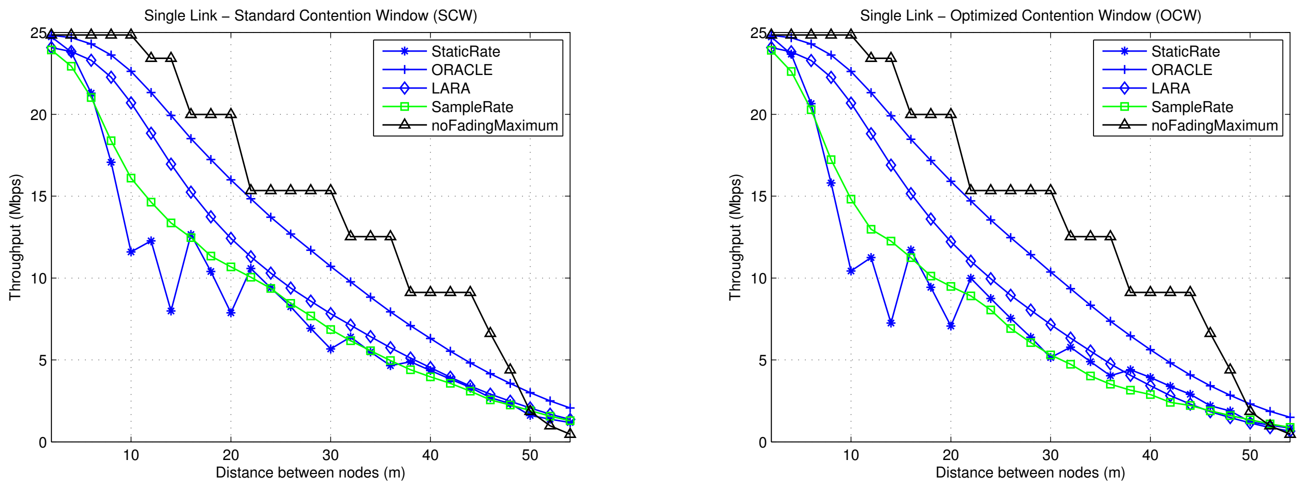
Algorithms considered for adapting the contention window are:

- *SCW* is the Standard 802.11 Contention Window adaptation (backoff) mechanism, which does not consider the cause of loss.
- *OCW (Algorithm 2)* is an Optimized Contention Window mechanism based on the work of Wu *et al.* [10]. Like SCW, it also does not use loss differentiation.
- *ROCE (Reset CW On Channel Error)* is a loss differentiation based contention window adaptation scheme. It sets the contention window to the minimum in case of channel error.
- *KOCE (Keep CW the same On Channel Error)* is also a loss differentiation based scheme. It maintains contention window at its current value in case of channel error (as opposed to doubling it like in the SCW algorithm).

**Algorithm 2** Optimized Contention Window (OCW) Adaptation [10]

**Require:** $retryCnt$
**if** $retryCnt == maxRetry$ **then**
  $cw = cw$
**else if** $successfulTx$ **then**
  $cw = max[cw/2, cwMin + 1]$
**else if** $failedTx$ **then**
  $cw = min[2 * cw, cwMax + 1]$
**end if**

We use QualNet v4.5 simulator [20] for our study. For modelling the wireless channel, we use the common two-ray propagation model with a path loss exponent of 3.38 (based




(a) SCW

(b) OCW

Fig. 1. Impact of loss differentiation on throughput performance in the single link case with different rate adaptation and contention window adaptation schemes. The "noFadingMaximum" curve in both plots is the case where Rayleigh fading is disabled in the simulation and provides an estimate of the maximum distance till which each of the rates remains best.

TABLE I
TRANSMIT POWER AND RECEIVE SENSITIVITY SETTINGS FOR COMPEX WLM54AG CARD

| | *Tx Power* | *Rx Sensitivity* |
|---|---|---|
| 6 Mbps | 23 dB | -93 dBm |
| 9 Mbps | 23 dB | -91 dBm |
| 12 Mbps | 23 dB | -89 dBm |
| 18 Mbps | 23 dB | -87 dBm |
| 24 Mbps | 23 dB | -78 dBm |
| 36 Mbps | 21 dB | -76 dBm |
| 48 Mbps | 19 dB | -74 dBm |
| 54 Mbps | 17 dB | -72 dBm |

on the non-line-of-sight indoor scenario in [21]) along with constant shadowing deviation of 4dB that is default in QualNet. With this channel model, the maximum distance between access point (AP) and client is 54m. We also use Rayleigh fading model with a low velocity of 1m/s to reflect WLAN scenarios with pedestrian mobility in the environment. We present results corresponding to 802.11a operation in the 5GHz band. 802.11a supports 8 rates: 6, 9, 12, 18, 24, 36, 48 and 54Mbps. Receive sensitivity values for different transmission bit-rates (modulation and coding schemes) and transmit power settings are taken from the Compex WLM54AG 802.11a card with an Atheros AR5212/5913 chipset (Table I). Throughout we use a fixed packet size of 1KB and each sender-receiver pair is presented with a CBR/UDP traffic at high load of around 25Mbps, which is close to the maximum throughput possible with 802.11a.

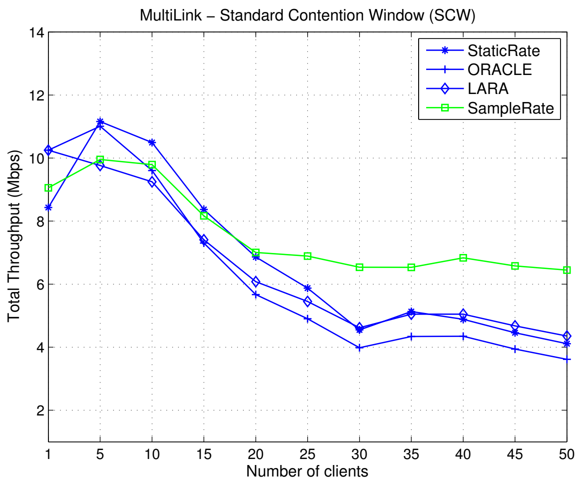
### *B. Results*

*1) Single Link:* We initially focus on the simple case of a single link between an AP and a client with varying distances of separation. The results are shown in Figures 1(a) and 1(b) corresponding to the use of SCW and OCW contention window adaptation schemes, respectively. Each data point in the plots is an average of 5 different simulation runs, each 5mins long. Comparing Figures 1(a) and 1(b), we observe that the contention window adaptation scheme chosen does not have any noticeable impact, as expected.

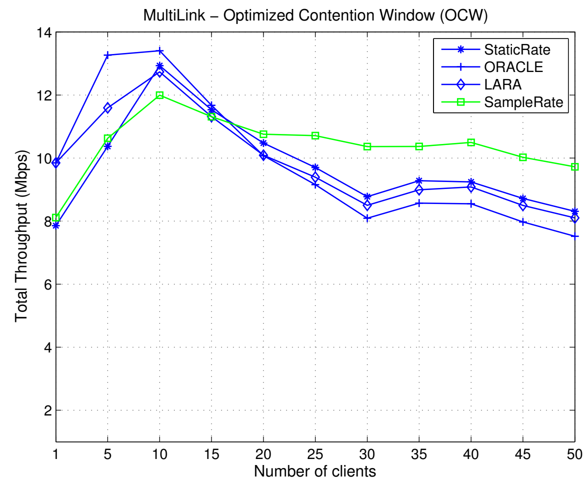
We now shift our attention to looking at the impact of various rate adaptation schemes. We observe that the StaticRate scheme performs the worst as it does not consider time-varying channel conditions — spikes correspond to distances at which rate is shifted down by one level, starting from 54Mbps at the smallest distance. ORACLE and LARA, though impractical, perform substantially better than SampleRate (the practical and commonly used scheme). Note that ORACLE and LARA are both RSSI based. ORACLE performs better than LARA, as expected, since it has perfect knowledge of the specific link. These results show that having a good estimate of receiver side channel quality information at the sender and using it for rate selection is key to superior performance in the single link case. The behaviour of the noFadingMaximum algorithm near the boundary of AP coverage area in Figure 1 is explained by Ren et al. in [22]. They show that the throughput rapidly decreases near the fringes of coverage in case of no fading, whereas the throughput starts to drop much earlier with Rayleigh fading but more gradually.

*2) Multi–Link:* In this section we study the more common case of multiple clients associated to an AP and communicating via the AP simultaneously. We model such cases by varying the number of clients associated to an AP from 1 to 50. Results are shown in Figure 2. Each data point in the plots is an average of 10 simulation runs with different random node placements for each specified value of the number of clients[1].

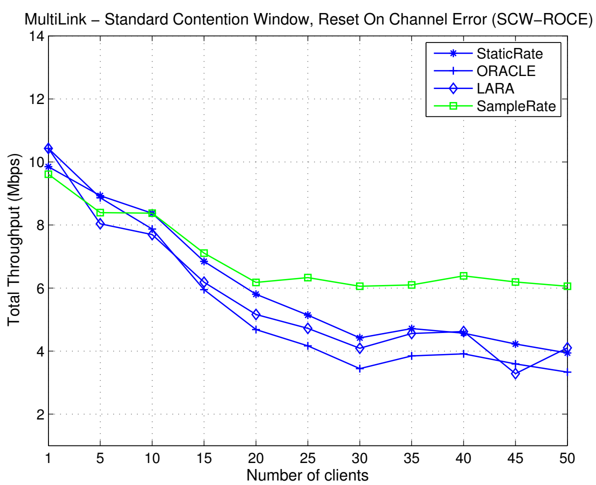
[1]As a consequence, the case with just one client does not correspond to any particular distance in Figure 1 but instead represents an average across different distances.



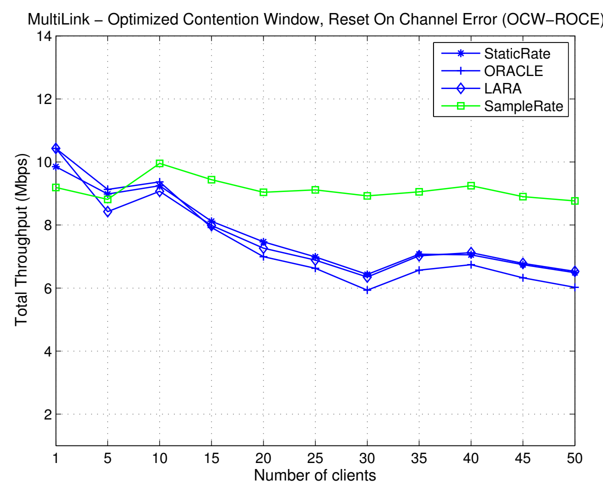

(a) SCW



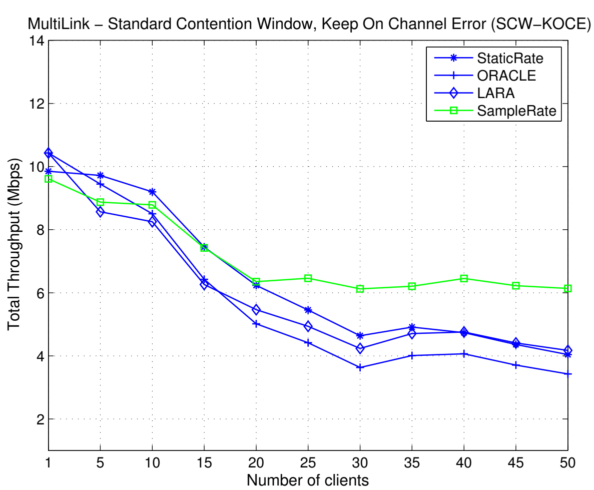

(b) OCW



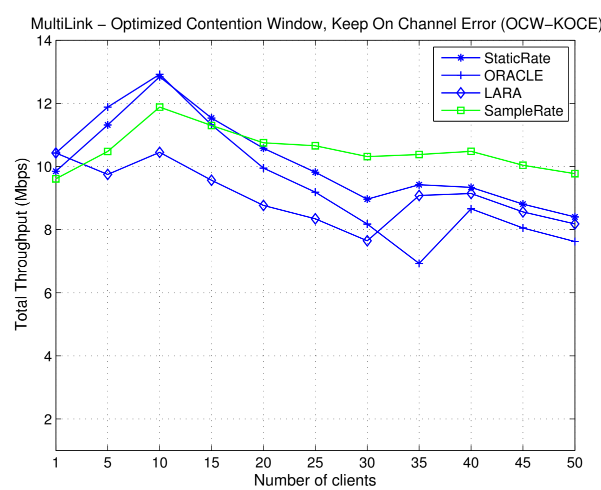

(c) SCW-ROCE




(d) OCW-ROCE




(e) SCW-KOCE




(f) OCW-ROCE

Fig. 2. Impact of loss differentiation on throughput performance in the multi-link case with different rate adaptation and contention window adaptation schemes.

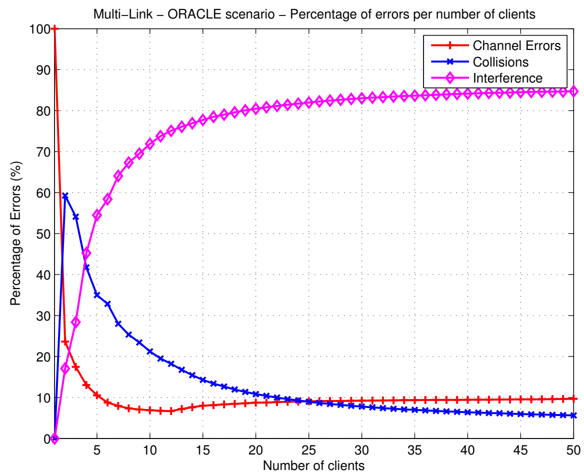



Fig. 3. Distribution of different kinds of losses with varying number of clients. Results shown here correspond to the combination of ORACLE and SCW but similar behaviour holds for all other combinations.

Overall, we observe that ORACLE-OCW outperforms all other schemes until a certain number of clients is reached. Thereafter the best throughput is achieved surprisingly with SampleRate. Note that neither of these schemes use loss differentiation though the former is not practical due to the assumption regarding availability of instantaneous receiver side RSSI on the sender side.

Loss differentiation based schemes (LARA with or without ROCE/KOCE) never provide superior performance. In fact, in most cases, these combinations perform even worse than StaticRate that does not adapt rate, especially when the number of clients exceeds a small number. This is in part because of the use of RSSI information obtained from the receiver end through successful ACKs for estimating channel quality. As the number of clients increase and share the medium, the channel quality information so obtained increasingly becomes stale and may no longer closely reflect the true state of the channel.

Unlike the single link scenario, ORACLE is not consistently the best performing scheme. This is because it only knows the best rate for maximizing the throughput of each link in isolation, but not the network as a whole. This agrees with the analysis by Radunovic *et al.* in [1], which shows that selfish rate selection performs poorly. In order to better understand this, we look at the distribution of losses with increasing number of clients (Figure 3). We observe that interference related losses (i.e., due to hidden terminals) dominate when there are more clients in the network. Using an optimal rate for each link in such cases only contributes towards increasing interference related losses. This suggests that a holistic view of rate selection is required and that sub-optimal rates may indeed be more effective in highly dense WLAN scenarios.

Moreover, all combinations using "OCW" (Figures 2 (b,d,f)) perform (or close to) the best for all rate adaptation schemes with the slight exception of StaticRate and SampleRate. For those schemes, the best performing alternatives are the ones using OCW-KOCE (Figure 2(f)). However, the difference between OCW and OCW-KOCE contention window adaptation schemes is about 1% in both instances. This shows that a link adaptation scheme that is unaware of the exact causes of loss (e.g., SampleRate-OCW) can perform on average almost as well as a loss differentiation based one (e.g., SampleRate-OCW-KOCE), suggesting that loss differentiation may not be critical for optimizing WLAN throughput performance.

## IV. *THEMIS*: Effective Link Adaptation without Loss Differentiation

As shown in Section III, RSSI measurement errors or lost ACK frames influence the performance of the RSSI based schemes. This is obvious in the high contention cases of Figure 2 that the RSSI based algorithms are the ones performing the worst. This suggests that it is helpful to use a direct indicator of receiver-side channel quality like RSSI only in low contention cases with few clients. In this section, we develop a scheme that considers RSSI in low contention cases in a way that is different from LARA while not relying on loss differentiation regardless of the level of contention. In essence, we synthesize an effective and novel link adaptation scheme that is devoid of loss differentiation by taking into account the various observations made in the previous section.

**Algorithm 3** *Themis*

**Require:** $RSSI\_est$, $contentionLevel$
**Ensure:** $cw$ $adapted$ $according$ $to$ $OCW.$

```
flag=FALSE
if currentRate is successful for less than T1 period then
    currentRate = currentRate
else
    flag=TRUE
end if
if currentRate fails for more than T2 period then
    flag=TRUE
end if
if flag==TRUE then
    if contentionLevel = low then
        rateToSample = highestRateBasedOnRSSI(RSSI_est)
    else
        rateToSample = selectRandomRate()
    end if
    TxTimeEst = sample(rateToSample)
    update_StatisticalTable(TxTimeEst, rateToSample)
    currentRate = bestRate(StatisticalTable)
end if
```

We call our proposed link adaptation scheme *"Themis"*[2] (Algorithm 3). *Themis* adapts both the contention window and

[2]In ancient Greek mythology, *Themis* had the ability to foresee the future and was one of the Oracles of Delphi (a temple); that ability made Themis the goddess of divine justice.

the transmission bit-rate. The contention window is adapted according to the OCW methodology by Wu *et al.* [10]. The rate adaptation is done using a statistical table that is created and maintained by occasionally sampling various possible rates (i.e., probing or actively transmitting at different rates) in order to determine the most effective rate that permits fastest transmission of data frames.

The main novelty of *Themis* is in the way the rate to be sampled is selected. *Themis* differentiates between low and high contention in the network and chooses a different strategy in each case. Current contention level in the network can be determined following the approach taken in WOOF mechanism by Acharya *et al.* [23] based on measurement of the channel busy time (fraction of time that the medium is utilized in a specific time interval) locally at each node. Once current contention level is estimated, we can distinguish between low and high contention cases using a threshold.

In low contention scenarios RSSI estimates obtained via receiver ACKs are usually still reliable since few clients try to occupy the medium and the likelihood of collisions/interference is low, as indicated by Figure 3. Therefore, when contention is low we choose the rate to be sampled based on RSSI estimate at the sender node as follows. We select the *highest* rate possible with the receive sensitivity that is immediately lower than the RSSI estimate describing the channel quality ($RSSI\_est >= RX\_sensitivity(rateIndex)$ according to Table I). On the other hand, in high contention scenarios RSSI estimate at sender side is not regarded as a trustworthy metric, so random rate selection for sampling is used instead. In either case, every time a rate is sampled, a statistical table is updated on the likelihood of the specific rate to be the fastest in successfully transmitting a typical data frame. The final rate selection is independent of the RSSI, and is only based on the aforementioned statistical table. This means that every time the rate adaptation algorithm needs to select a new rate to use, it looks up this table and selects the rate with the highest probability.

Finally another feature of *Themis* is how often and under what circumstances should it sample another rate in order to select a new one based on the updated statistics. Our aim is to maintain a rate that is successful while at the same time we want to adapt quickly to changes in the environment. Moreover, we want to minimize the overhead of sampling and avoid unnecessary actions that would cause overhead. To satisfy these objectives, we define two parameters $T1$ and $T2$ as shown in Algorithm 3. So long as a rate is successful sampling another rate is delayed for a period $T1$. On the other hand if the chosen rate is continuously failing for a period $T2$ then a new rate will be sampled. We empirically found that $T1 = 10sec$ and $T1 = 1sec$ offer the best balance between adapting quickly to environmental changes and keeping overhead low.

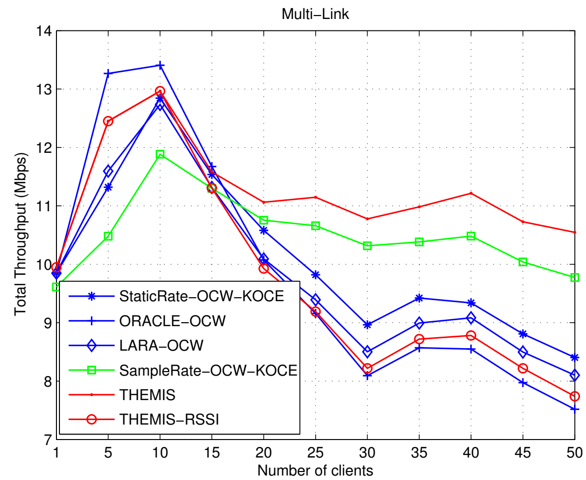



Fig. 4. Throughput performance of *Themis* in the multi-link case relative to the top performing alternatives from the loss differentiation study.

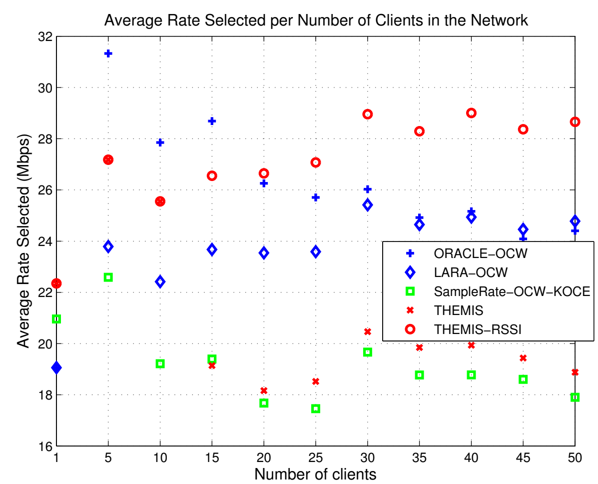



Fig. 5. Average rate chosen by *Themis* and the top performing alternatives from the loss differentiation study with varying number of clients.

## V. *THEMIS* EVALUATION

In Figure 4, the throughput performance with *Themis* is compared with the best performing variants from the multi–link study in Section III (see Figure 2). Only ORACLE–OCW performs slightly better than *Themis* in the low contention scenario since it has perfect knowledge of the exact channel quality and chooses the rate to use accordingly. However, when the interference increases (high contention) the RSSI and loss differentiation based schemes (ORACLE–OCW, LARA–OCW, StaticRate–OCW–KOCE and SampleRate–OCW–KOCE) are no longer effective in a dense multi–link scenario. Figure 5 shows the average bit-rate chosen by various schemes including *Themis* with varying number of clients. Both Figures 4 and 5 show the adaptability of *Themis* to varying levels of contention and distribution of losses (as previously shown in Figure 3). Comparing the throughput results of *Themis* with those of standard 802.11a/b/g and SampleRate algorithm (SampleRate-SCW) from Figure 2, we observe that *Themis* does 60% and 40%, respectively, better in high density settings.

In order to validate the hypothesis that selecting the rate based on the RSSI in high contention scenarios would not be fruitful, we consider a variant of *Themis* that is based on RSSI (Themis-RSSI). Themis-RSSI always selects the rate to be sampled based on the RSSI. From Figure 4, we can see that it performs poorly like the RSSI and loss differentiation based schemes do in the high contention case. At the highest level of contention, the throughput achieved with Themis-RSSI is 27% worse compared to *Themis*.

This can be attributed to the use of stale and untrustworthy RSSI estimates in high contention scenarios. As shown in Figure 5, RSSI based schemes (ORACLE, LARA and Themis-RSSI) tend to use higher rates on average at higher levels of contention, further exacerbating the hidden terminal problem and increasing interference related losses. We can see that the worst performing schemes on average (LARA-OCW and ORACLE-OCW) mostly select similar high average rates as shown in Figure 5 irrespective of the number of active clients in the network. Such rates limit the transmission range of nodes using the higher rates, thus increasing the number of hidden terminal related interference losses. On the other hand, SampleRate-OCW-KOCE, which performs better than both of these schemes, selects the lowest average rates. This shows that the probability of successfully transmitting is higher at lower rates than with higher ones in higher contention scenarios. The improved performance of *Themis* stems from its ability to select on average higher average rates than LARA-OCW and ORACLE-OCW in low contention scenarios, and then drop the rates with increasing number of clients, reaching similar rates as SampleRate-OCW-KOCE. Figure 5 also validates the observation that RSSI does not allow for a “finegrained differentiation in the range relevant to bit-rate selection”, made by Ramachandran et al. in [5], where a rate adaptation scheme optimized for congested WLANs is proposed.

We also examined the fairness of these schemes using the Jain′s fairness index [24]. *Themis* performs on average about 10% better than the rest of the schemes in terms of fairness. This is especially true in high contention scenarios because *Themis* uses lower rates on average, increasing the number of successful transmissions for all nodes. Additionally, as Figure 5 shows, *Themis* manages to use higher rates when appropriate, which is important to achieve high aggregate throughput and fairness.

Overall, our results show that actions chosen in response to losses are more important compared to having an accurate mechanism to discriminate between different types of losses. For a link adaptation scheme to be effective, actions it takes when losses occur need to be holistic rather than being solely dependant on the exact cause of loss.

## VI. Conclusions

In this paper, we have examined the impact of loss differentiation on the performance of link adaptation in 802.11 infrastructure WLANs, focusing on adaptation of transmission bit-rate and contention window. While loss differentiation can be helpful, it is also a difficult problem given the limited feedback available to the sender in 802.11 networks. Motivated by this observation, we have developed a novel link adaptation scheme called *Themis* that does not rely on loss differentiation but still is able to outperform schemes that do, especially in high contention scenarios. Our work shows that not knowing the exact cause of loss is not an impediment to effective link adaptation. Approximately knowing the cause of loss or even just the distribution of losses is sufficient. Actions taken in response to losses are, however, more crucial and they ought to be holistic and not solely dependant on the exact cause of loss. In this paper, we have limited our attention to legacy infrastructure-based 802.11 WLANs. It is worthwhile to investigate whether our conclusions hold in 802.11 based ad hoc or vehicular networks and in 802.11n networks.

It remains to be examined if such a holistic adaptation scheme can be even more effective in the IEEE 802.11n case, since there are even more parameters to consider. Finally, it is also interesting to examine if loss differentiation is effective in cases of other kinds of networks, like ad-hoc or vehicular networks.

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