Determining 802.11 Link Quality with Passive Measurements

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***Abstract*—Unlike a wired link, a wireless link changes according to the physical environment and the network traffic in the surrounding area. The link quality, capacity and reliability are dependent on the MAC layer parameters and the channel conditions. In this work, we present a new passive link quality measurement tool and study the effects of modulation rate changes, interflow and intraflow interferences on the wireless link. We observe the channel conditions (RSSI in both directions), retries, and various basic metrics to determine their usefulness in certain conditions. We found that RSSI is not a good metric for link quality since it does not correlate with the measured throughput. Other factors, such as modulation rate settings and the topology setups are also detailed in this paper.**

I. Introduction

IEEE 802.11 wireless networks are widely used in homes, airports and for long distance wireless links [1]–[3]. In many of these applications users pay to use the wireless network and therefore expect a minimum Quality-of-Service (QoS). Since the wireless medium does not provide any protection from external electromagnetic waves, transmission power and modulation rate of a transmitted 802.11 packet play a big part in wireless link quality and impact other aspects of user QoS. In order to support the minimum QoS required by the users, future wireless networks need sophisticated link quality monitoring systems that work with QoS control mechanisms to adapt the network to changes in the external disturbances. In this paper, we introduce a novel link quality measurement tool, which can be used to support a wide range of network QoS controls.

One way to increase the QoS experienced by users is to change link modulation in response to external wireless disturbances [8]–[11]. Link rate adaptation algorithms adjust the physical layer modulation to achieve high link rate and high link quality. At lower modulations, links are more robust and can handle packets with low signal-to-noise ratios (SNR). On the other hand, at higher modulations, link bit-rates are higher, but links are less robust and can only operate at higher SNR. Current link rate adaptation algorithms use a single metric to adjust the link rate. ARF [9] and ONOE [8] use observed frame loss errors to adjust link rates. SampleRate [11] uses observed throughput, while others [10] use SNR measurements. However, as it was pointed out in some recent studies [12], hybrid approaches are required because algorithms that rely on frame loss alone implicitly assume that all frame losses occur due to changes in received SNR and ignore the fact that frames may be lost due to packet collisions in the MAC layer.

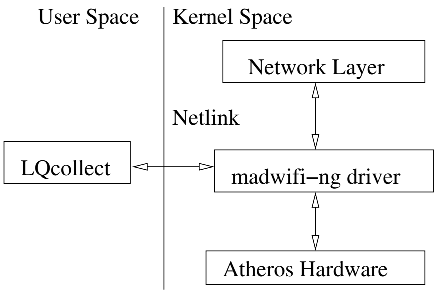
Our measurement tool can be used to support a wide range of link rate adaptation algorithms. We use three indices to track link quality. First, we keep track of the received signal strength indicator (RSSI), which gives us information about the link's SNR. If the link transmittted data on its own, high RSSI has a high correlation to high SNR and low frame error rates. Second, we keep track of the percentage of lost frames. If RSSI is high, a high frame loss rate is correlated with network congestion and 802.11 packet collisions. Third, we track the link's goodput and throughput. Goodput is the number of successful frames from higher layers over time while throughput is the actual number of transmitted frames (including retries) sent over time.

We perform several experiments using our passive measurement tool to gain new and reaffirm old insights into the behavior of 802.11 wireless networks. We have found that RSSI and goodput do not have a strong correlation. For example, collisions can introduce approximately 30-40% of frame errors in some networks even with good channel conditions. The 802.11 performance anomaly [13] can also be seen using our measurement tool. The anomaly manifests itself when one wireless link is at a higher modulation (i.e., 54Mbps) than another (i.e., 6Mbps). With these link modulations, the higher modulation rate link will have an effective throughput as the same as the lower modulation link.

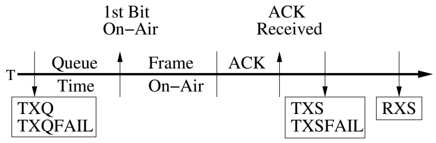
The rest of the paper is organized as follows: Section II describes our software measurement tool and the link quality metrics we obtain with the tool; Section III describes the experimental setup we used to evaluate the tool. Section IV shows the observations we have made with our measurement tool. Next, we review some related studies in 802.11 link quality measurements.

A. Related Work

An ORBIT lab study [12] looked at the effects of rate adaptation in their testbed. Their results only show the effects of rate adaptation in terms of goodput and throughput, while we can look at per frame retransmissions and per modulation rate analysis. Our passive measurement tool can also be used in larger experimental testbeds to give a detailed frame by



(a) Measurement Tool Design



(b) 802.11 Frame Events

Fig. 1. The Measurement Tool

frame analysis to measure metrics like the Wireless Overhead Multiplier [14].

An indoor testbed study [15] evaluated the relationship between SNR, distance and packet loss. Unlike our tool, they considered only packet losses and not the number of retransmissions needed to transmit that packet at the link layer.

Other tools were created that focused on wireless monitoring and sniffing [16]–[19]. Our tool enhances the wireless sniffers by gathering information needed to determine the quality of a link. The monitoring tool, EAR [20], measures the link quality by using hybrid passive and active measurements. In our study, we are concerned more about how the various parameters affect the wireless link and we study the wireless link in a passive measurement setup rather than introduce more traffic into the network.

Previous researchers have looked into link quality measurements as a metric for routing and rate adaptation. Our passive link quality measurement tool can be used to compliment these works. The routing metric, ETX [21], is based on the forward and backward probability of frame losses. In our paper, we show that frame losses can be misleading as a link quality metric. ETX does not account for heavily loaded links which may have a good link quality but very low throughput. By enhancing the ETX metric with our link quality measurements, we can look at not just the number of frame losses but also the number of retries needed per frame.

Modifications to the device drivers, which are similar to ours, have been made in the past [22]. However, their purpose is to verify assumptions made for 802.11 models. Our purpose is to determine the quality of a link.

II. Our Measurement Software

We have implemented our measurement framework in the Linux kernel [23], using the madwifi-ng [8] wireless device driver. We modified the madwifi-ng device driver so that it reports certain 802.11 events, which we use to derive link quality statistics, Fig. 1(a). A userspace program communicates with the modified driver through the NetLink library [24] and records these events. The userspace program either processes the message records locally on the machine, or sends them to a database server, which can take global actions based on the reports. For this paper, all events are locally processed.

The modified driver reports the following three event types to the userspace program: frame enqueue (`TXQ/TXQFAIL`), transmission status/buffer reaping (`TXS/TXSFAIL`) and receive status reaping (`RXS`). Fig. 1(b) shows the temporal relationships between the events. Each of the events corresponds to an action taken by the driver in response to a frame transmit request or frame reception:

- Frame enqueue (`TXQ/TXQFAIL`) event is generated when the device driver receives a frame from the higher layers and the frame is either placed into the outgoing hardware queue of the wireless interface (TXQ), or dropped because the queue is full (TXQFAIL).
- Frame transmission status (`TXS/TXSFAIL`) event is generated when an acknowledgment was received (`TXS`) or a timer has expired (`TXSFAIL`). Due to the nature of the madwifi-ng driver, this event occurs some time after the ACK is received. If no ACK is received, this event occurs after the ACK timeout with a transmit error status. Included with the status event are the number of retries used to transmit the frame.
- Frame receive status (`RXS`) event is generated after a MAC frame or an ACK is received. Due to the nature of the madwifi-ng driver, the `RXS` event may be delayed from the time a packet was received. However, each `RXS` event is timestamped by the driver as soon as the hardware receives a frame or an ACK, so this timestamp can be used to identify the exact time a frame has been received.

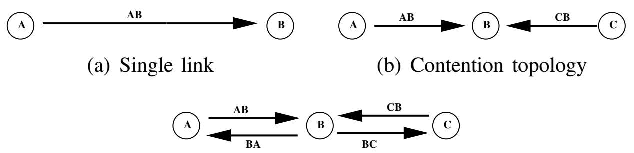
Before sending the events to the userspace, the modified driver timestamps each message. In addition to the timestamp, the modified driver also attaches the received signal strength indicator (RSSI) to each reported event. This value is the signal power of the frame received plus the interference power minus the noise floor (SINR).

On the transmitter side, a data frame has to be followed by an ACK in order for the frame to be counted as successful. RSSI ACK is the RSSI of this received ACK frame at the transmitter. It has the same rules as the RSSI metric but only applied to ACK frames.

The event messages also record the frame headers (MAC to Transport layer), the number of retries used per frame and modulation rate used in the transmitted frame. With the headers, we can determine the type of 802.11 frame and the source and destination of the frame. The retry count will allow us to calculate how many times the frame is transmitted over the air before an ACK is received.

A. *Link Quality Metrics*

1) Received Signal Strength Indicator: RSSI is the received power level for a frame. For the Atheros wireless cards, RSSI



(a) Single link (b) Contention topology

(c) Multihop topology

Fig. 2. Experimental Topologies

is the signal plus interference power (in dBm) minus the noise floor. Some previous works [15] showed that the received power can be a relative metric for the quality of the link.

2) Frame Error Rate: We define FER in this paper as the ratio between the number of frames, including the number of retries on the wireless channel over the number of successfully acknowledged frames:

$$FER = \frac{\text{\# of failed tries}}{\text{\# of failed tries} + \text{\# of successful tries}} \quad (1)$$

3) Goodput: Goodput can be used as a link quality metric to show how fast frames can be sent out reliably. It takes into account the transmission time of a frame and the length of the frame. Goodput is calculated with:

$$Goodput = \frac{\text{\# of bytes transmitted successfully}}{\text{\# seconds taken to transmit frames}} \quad (2)$$

Our software measurement tool also keeps track of link layer throughout, which is obtained by considering all frame transmissions (as opposed to goodput, which only considers succesful frame transmissions). Throughput is calculated by using the extra information available `TXQ/TXQFAIL` messages. Due to space restrictions, we do not show the link layer throughput calculations or results.

III. Testbed Setup

In all of our experiments, we use HP nc6000 laptops with the Atheros wireless cards. We run Fedora Core 6 with the 2.6.20 kernel and the madwifi-ng [8] wireless device driver. Since we run our experiments indoors, we use 802.11a channels to limit the amount of interference from other wireless networks. In the area where we performed our experiments, we discovered at least 15 802.11b/g access points/networks in the lab area. There are no 802.11a access points. We have noticed one 802.11a capable station periodically probe our chosen channel for access points. However, after reviewing the experimental results, we were assured that the frames sent had no significant impact.

We keep the default number of tries per frame, which is set to 11 in the madwifi-ng driver. We have turned off rate adaptation in this study. All modulation rates are fixed and do not vary throughout a scenario run to ensure accurate base results that are not influenced by changes in the rate adaptation protocols. We also turn off multi-rate retries, which allow each successive retry of a single frame to be sent at different modulation rates. Table I summarizes the software and hardware setup in our testbed.

TABLE I
TEST-BED PARAMETERS

Laptop Parameters	**Value(s)**
Linux Kernel	2.6.20
Wireless Device Driver	madwifi-ng svn r2492 trunk
Traffic Generator	MGEN v4.0
Experiment Parameters	**Values(s)**
802.11 mode	802.11a (STA and AP)
Channel/Frequency	Channel 50, 5.25GHz
Maximum Tries Per Frame	11
Transmission Power	15dBm
Rate Adaptation	None

A. Topologies

Our topologies range from two to three nodes to focus on single wireless link behaviors and minimize interference. The single link topology, Fig. 2(a), is used as a check for upper bounds on capacity/goodput, frame queuing and retries in a non-interfering environment. We use the contention topology, Fig. 2(b), to study contention link quality around gateways. Finally, we use a multihop topology, Fig. 2(c), to simulate a conversation between two nodes in a multihop environment. We generate traffic using the MGEN traffic generator [25] with different constant bit-rate UDP traffic depending on the scenario.

IV. Experimental Results

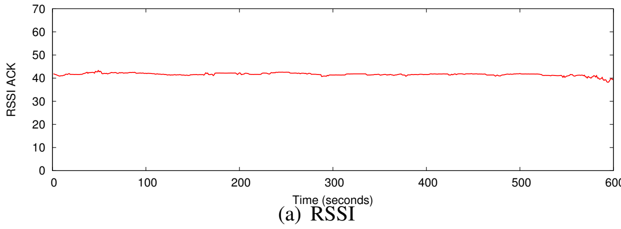
In this section, we present some experimental results from our link quality measurement tool. Due to space constraints, we only show a small subset of the experimental results.

A. Single Link at 54Mbps Modulation Rate

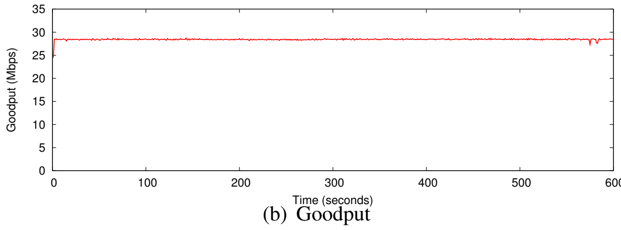
For the base case, we look at a single link with fixed modulation rate of 54Mbps. The setup is shown in Fig. 2(a). The application sending rate is set to 36Mbps (using UDP). This allows us to test the actual capacity of the link, which is approximately 28Mbps as shown in Fig. 3(b) The average frame error rate of the whole test was 1.073e-3. The maximum frame error rate is 0.01 and minimum is 0. We can say that this link has high quality. We are getting approximately the maximum practical sending rate on the link and have negligible frame errors.

B. Modulation Rate Affects the Link Quality

Using the same link as the previous scenario, we varied the fixed modulation rate from 54Mbps to 36Mbps to 6Mbps. The results are shown in Fig. 4. At 54Mbps, the goodput is the highest (near 28Mbps) with the 6Mbps modulation rate at 5.5Mbps. Notice the gap between the theoretical throughput (modulation rate) and the experimental throughput. This can be explained by the 802.11 overheads including the PLCP, DIFS, SIFS, backoff and ACK transmission time.



(a) RSSI



(b) Goodput

Fig. 3. Single Link at 54Mbps Modulation Rate

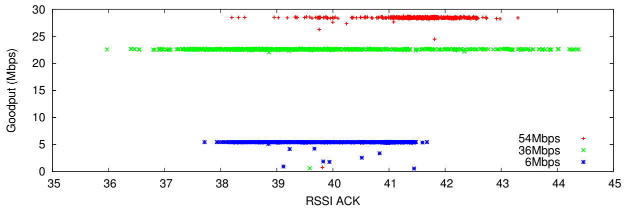


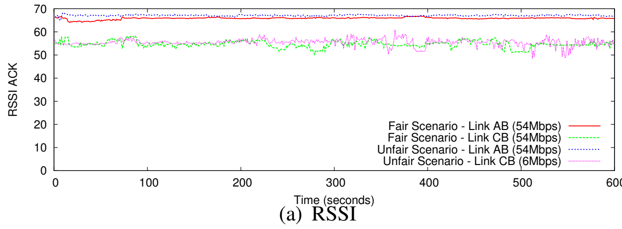
Fig. 4. RSSI vs. Goodput Differences in Modulation Rates

C. Contention Topology Results

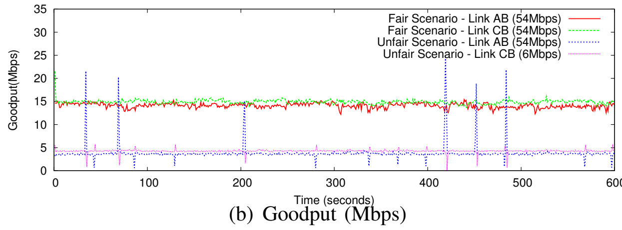
There are two scenarios shown in the figures of Fig. 5 using the intraflow topology, Fig. 2(b). The first scenario is called the "Fair Scenario" where both links' modulation rate are set to 54Mbps. The second scenario is called the "Unfair Scenario" where one link is set to 54Mbps and the other is set to 6Mbps. Fig. 5(a) shows the RSSI link quality is similar in the two scenarios.

The difference between the two scenarios is goodput, Fig. 5(b). In the "Fair Scenario", both links get an equal share of the channel resource. In the "Unfair Scenario", both links are getting equal goodput, but not equal time. Notice, that the Link AB should be able to send at 54Mbps but it is only getting as much bandwidth as Link CB. This can be explained by 802.11's channel access fairness. Since both links are fair in the way they access the channel, Link CB will definitely take more time to send the same amount of data as Link AB. Our observations are consistent with the previous work in the 802.11 anomaly [13].

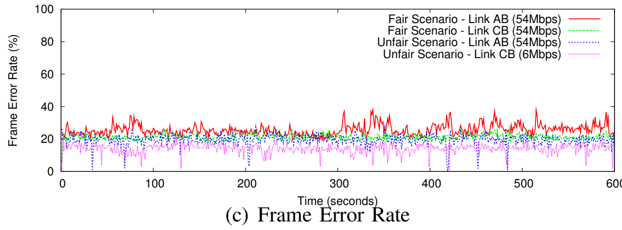
Fig. 5(c) shows the frame error rates (FER) for the two different scenarios. Both 54Mbps links in the "Fair Scenario" case have a high frame error rate (20% to 30%) due to frame collisions rather than noise. In the "Unfair Scenario" case, the FER for Link CB (6Mbps) is always lower than for Link AB (54Mbps) because of the differences in modulation rate. Intuitively, 54Mbps links would have lower FER since their frames spend less time on the air than 6Mbps frames. However, the 6Mbps frames actually have lower FER due to the more robust encoding scheme, which allows them to overcome most errors caused by collisions and noise.



(a) RSSI

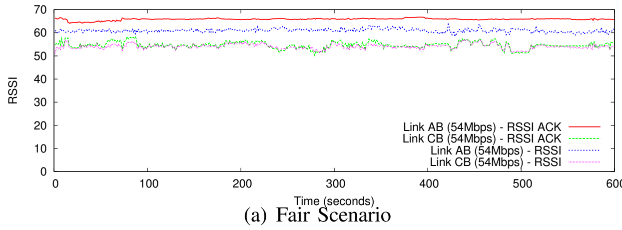


(b) Goodput (Mbps)

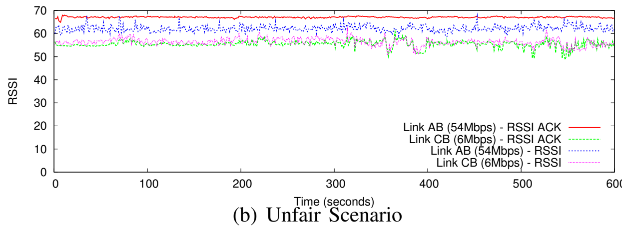


(c) Frame Error Rate

Fig. 5. Inter-Flow Comparison on Different Link Modulation Rate



(a) Fair Scenario



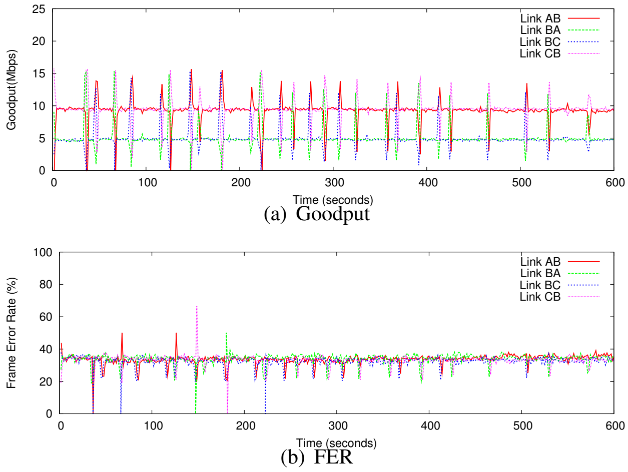
(b) Unfair Scenario

Fig. 6. Inter-Flow Comparison of RSSI and RSSI ACK

Fig. 6(a) and Fig. 6(b) show the RSSI and RSSI ACK values for the fair and unfair scenarios. The RSSI ACK is the signal strength read from the ACK frame at the transmitter, while the RSSI is the signal strength read from the DATA frame at the receiver. Link CB has very symmetrical signal strength, but Link AB does not.

D. Multihop Topology Results

In the multihop topology, Fig. 2(c), nodes A and C are sending traffic to each other. Data traffic from either node is relayed through node B. In this scenario, all links are set fixed to 54Mbps. Link CB and Link BC have slightly lower RSSI



(a) Goodput

(b) FER

Fig. 7. Multihop Topology

than Link AB and BA . Fig. 7(a) shows the goodput. The channel is contended fairly by all three nodes. The 802.11 protocol has a channel access fairness, so Link BA and Link BC share the same channel access probability since they are from node B. This can be seen by the fact that Link BA and Link BC are both halved the goodput than either Link AB or Link CB. Fig. 7 shows the frame error rate of all four links. Since all four links have similar characteristics, their frame error rates are similar.

V. Conclusions

We have implemented a novel link quality measurement tool and used it to evaluate 802.11 links in our indoor testbed. Our tool provides us with three metrics for wireless link quality: frame error probability, signal strength and link goodput. This tool can be used for hybrid link rate adaptation [12] approaches, or with network tools, which monitor, report and react to variable conditions in the network [26]. Using this tool we have observed the link quality of a normal single link, the performance anomaly in an interflow scenario and the link quality in a multihop topology. For our future work, we will deploy the tool in regular testbeds to see how link qualities behave in uncontrolled environments.

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