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Analysis of IEEE 802.11b/g Card Behavior in Multirate Ad-hoc Networks

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Abstract. In multirate ad-hoc networks, mobile stations usually adapt their transmission rates to the channel conditions. This paper investigates the behavior of IEEE 802.11b/g cards in a multirate ad-hoc environment. WLAN network cards from different vendors are analyzed. The theoretical upper bound estimation of the throughput in multirate ad-hoc networks is derived. The measurement scenarios and obtained results are presented. For result validation the theoretical and experimental values are compared.

1 Introduction

Wireless networks based on the IEEE 802.11 family of standards have become widespread in recent years. Even though Access Points are being deployed both at home and public places, it is the ad-hoc mode of 802.11 which is expected to become increasingly popular in the near future. One of the features of 802.11 devices, which can significantly increase their performance, is the use of adaptive multirate transmission schemes.

All four currently used IEEE standards support multirate, i.e., 802.11 [5], 802.11a [6], 802.11b [7], and 802.11g [9]. Each of them allows different speeds in the uplink and downlink directions depending on current physical conditions of the radio channel.

The theoretical performance of multirate capable devices has been measured extensively but practical results vary. This is not only due to different testbeds and radio conditions, but also because of vendor implementations.

A good example of this problem can be found in [17], where several IEEE 802.11 cards from different vendors were analyzed. The stress was laid on MAC implementations and hardware delays. Two meaningful conclusions appeared. First of all, it was shown that a notable unfairness in rate selection appears among different commercial cards and, furthermore, that the unfairness is a result of different hardware/firmware implementations. It is expected that a similar situation will be observed in multirate IEEE 802.11b/g ad-hoc environments.

The aim of this work is to show the differences in performance and interoperability of multirate IEEE 802.11b/g cards of the following vendors: Linksys, Lucent and Proxim. All cards were operating in ad-hoc mode. The concept of the presented scenario was to capture and analyze FTP traffic sent by a server to two clients.

The rest of the paper is organized as follows. The state of the art is presented in Section II. A mathematical model for calculating transmission rates in 802.11 is described in Section III. The measurement scenarios and results are shown in Sections IV and V, accordingly. Section VI gives a validation of the achieved results. Section VII closes the paper summarizing the main conclusions.

2 State of the Art

The IEEE 802.11 family of standards does not provide any method of automatic rate selection in the presence of multirate capable devices. Because of this, there are many methods of choosing the appropriate rate and it is up to the card vendors to decide which one to use.

The co-operation of cards of different standards is possible because the preamble and header of each frame is sent with the basic rate – understandable by all cards. Only the payload can be sent at higher rates (cf. Table 1). This is especially important for 802.11b and 802.11g co-operation.

Table 1. Comparison of Preamble, Header, and Payload Rates

Mode (lp/sp: long/short preamble)	**Physical Layer Convergence Procedure (PLCP)**		**Payload [Mbps]**
	Preamble [Mbps]	*Header [Mbps]*	
802.11	1	1	1 or 2
802.11b lp	1	1	1,2, 5.5 or 11
802.11b sp	1	2	2, 5.5 or 11
802.11g lp	1	1	1, 2, 5.5, 6, 9, 11, 12, 18, 22 (optional) 24, 33 (optional), 36, 48 or 54
802.11g sp	1	2	2, 5.5, 6, 9, 11, 12, 18, 22 (optional) 24, 33 (optional), 36, 48 or 54

It must also be noted that transmission rates are not linear. Therefore, e.g., an 11 Mbps link with a delivery ratio of just above 50% is always better than a 5 Mbps link.

Multirate algorithms can be based on statistics. The ARF (Auto Rate Fallback) [1] protocol is perhaps the most commonly used (and possibly the first such algorithm). To determine the channel quality, ARF utilizes link layer ACK frames (i.e., the Frame Error Rate, FER). After a given number of consecutive ACKs have been received, the transmission rate is increased. The loss of a similar number of ACKs causes the node to decrease the transmission rate. The main advantage of ARF is that it is simple to implement and does not interfere with the 802.11 standards. However, it is slow to adapt to channel conditions – it tries to change the rate even for stable links, and can mistake collisions for channel losses.

Most popular WLAN cards currently use the Atheros chipset which (under Linux) can be configured with the innovative MadWiFi driver. This driver implements three different rate adaptation algorithms: Onoe [12], AMRR (Adaptive Multi Rate Retry) [10], and SampleRate [2]. Onoe, the default algorithm, is based on ARF and looks for the highest bitrate that has a loss rate less than 50%.

A binary exponential backoff scheme enables AMRR to work well for high latency systems. SampleRate uses aggressive probe packets to estimate the optimum transmission rate.

A different approach to multirate selection is presented by SNR-based algorithms such as RBAR (Receiver Based Auto Rate) [4]. In this solution, the receiver measures the SNR value of the received RTS and uses the CTS frame to inform the sender of the desired rate. This allows for very fast adaptability, but requires changes in the IEEE 802.11 standard and the constant use of the RTS/CTS mechanism.

A very efficient approach seems to be the OAR (Opportunistic Auto Rate) protocol [15]. It utilizes the coherence times of good channel conditions to send high-rate multi-frame bursts. This is similar to the TXOP (transmission opportunity) feature of 802.11e [8]. OAR has low overhead and can increase fairness in the network. However, it also requires changes to the IEEE 802.11 standard.

Despite many theoretical analyses of 802.11 performance, not much study has been done to measure interoperability performance between cards belonging to different vendors. A recent analysis can be found in [17] (closely related to the work done in [16]). The authors measure the performance of six 802.11b cards (in infrastructure mode) to determine whether they adhere to standards. Their main conclusion is that most of the unfairness between commercial cards is due to the hardware/firmware implementations, rather than channel properties. Furthermore, they state that cards belonging to the same vendor exhibit better fairness.

Garoppo et al. have presented an interesting comparison between analytical, simulation and experimental results for two 802.11b cards from different vendors [3]. Their results show high correlation between the modeled, simulated and measured values. However, they also notice a meaningful difference in the performance of the two cards in an infrastructure network.

Performance measurements of the saturation throughput [1] of five different IEEE 802.11b access points (APs) can be found in [14]. The upper bound of the AP throughput was considered. The three major observations are as follows. Firstly, an increase in the load offered to the AP's Ethernet interface does not always result in throughput increase. Secondly, for several APs, if the offered load exceeded their bridging capabilities they reduced their downlink throughput. Finally, better performance in certain directions was observed. The overall conclusion was that meaningful differences in the maximum saturation throughput exist for APs from different vendors.

3 Mathematical Model

The mathematical model derived in this section is based on work presented in [11] and [13]. The aim of this model is to obtain the theoretical upper bound estimation of the throughput in a multirate ad-hoc environment.

We consider a situation in which station i starts its transmission of a DATA frame of length l to station j at time t . The basic assumptions are that data frames are of equal length, no hidden stations appear and all data frame transmissions are

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[1] We define throughput as the ratio of the data transmitted in the link layer (including frame headers) to the time needed to deliver the data from one node to another.

independent. Furthermore, the MAC performance is only evaluated, pure DATA/ACK mode is assumed and all currently transmitting/receiving stations remain stationary.

Let us assume the following notation: A is the set of all stations in a BSS, N is the total number of stations in A, l is the length of the data frame, l_{ACK} is the length of the ACK frame (all measured in normalized time units). Other parameters are as follows: β is propagation delay, S is overall system throughput, T_S (T_C) is expected time interval between periods when the channel is idle for a DIFS (Distributed Inter-Frame Space) period, within which at least one successful (collided) transmission took place.

A successful transmission must fulfill the following conditions: (a) the sender and the receiver stations are not hidden from each other, (b) no other station being within the range of the receiver starts its transmission within the time period $[t-\beta, t+\beta]$, (c) no other station being within the range of the sender receives any successful frame within the time period $[t-\beta, t+\beta]$.

Once a channel is sensed idle for a DIFS interval, time needed for the data frame destined to station *j* to be generated at station *i* is assumed to be exponentially distributed with a rate λ or $G(i,j)$ (equivalent terms). As a consequence, the total rate for a common channel in a single BSS is $N(N-1)\lambda$ or $G=\sum_{i,j} G(i,j)$.

Simple observation shows that:

$$T_C \geq 1/G + l + DIFS + \beta \tag{1}$$

$$T_S = 1/G + l + SIFS + l_{ACK} + DIFS + \beta \tag{2}$$

where $1/G$ is the expected time until the beginning of a transmission of the first frame after the channel was sensed idle for DIFS.

Let us denote by $p_s(i,j|m,n)$, where $m,n \in A$, the probability of a successful data frame transmission from station *i* to station *j* only under the condition that, after a DIFS interval, a data frame transmission between stations *m* and *n* occurs. As a result, the effective lower bound estimation of the expected number of successful transmissions for a Poisson process can be given as follows:

$$p_S(i,j) = e^{-N(N-1)\lambda\beta} \tag{3}$$

The probability that station *i* starts its transmission to station *j* before the end of an idle period is $\frac{G(i,j)}{G}$. The probability that station *i* starts its transmission to station j before β (after the idle period was interrupted by a transmission between stations m and n) is given by $\frac{G(m,n)}{G}\left(1-e^{-\beta G(i,j)}\right)$.

Let us denote by $S(i,j)$ the throughput between stations i and j and, because $l_{ACK} + SIFS << l$, let us assume that $T_C \approx T_S$. As a consequence we get:

$$S(i,j) \approx \frac{p_s(i,j)\frac{G(i,j)}{G} + p_s(i,j)\left(1-e^{-\beta G(i,j)}\right)\sum_{(m,n)}\frac{G(m,n)}{G}}{T_S} = \tag{4}$$

$$= \frac{p_s(i,j)\frac{1}{N(N-1)} + p_s(i,j)\left(1-e^{-\beta\lambda}\right)\frac{N(N-1)-1}{N(N-1)}}{1/G + l + SIFS + l_{ACK} + DIFS + \beta}$$

Denoting the overall upper bound of the system throughput as $S = \sum_{(i,j)\in A} S(i,j)$ we get:

$$S = N(N-1)\frac{p_s(i,j)\frac{1}{N(N-1)} + p_s(i,j)\left(1-e^{-\beta\lambda}\right)\frac{N(N-1)-1}{N(N-1)}}{1/G + l + SIFS + l_{ACK} + DIFS + \beta} = \tag{5}$$

$$= \frac{p_s(i,j) + p_s(i,j)\left(1-e^{-\beta\lambda}\right)N(N-1)-1}{1/G + l + SIFS + l_{ACK} + DIFS + \beta}$$

4 Measurement Scenarios

The measurements of the performance and interoperability of 802.11b/g wireless cards from different vendors were carried out in usual office conditions. The tested cards were: Linksys WPC-11, Lucent Silver PC24E, and Proxim 8480-WD. All cards worked in ad-hoc mode. Their output power was set to 30mW. The card vendors do not provide information on the type of multirate algorithms used.

In the considered scenario, the testbed consisted of three homogenous stations (see Fig. 1): one FTP server (Station C) and two clients (Stations A and B). Both clients, when connected to the server, began downloading a 1GB file what allowed to capture more than 50 thousand FTP frames transmitted from the server to the clients.

Station B was mobile. It increased its distance from the server. Station A was stationary. All measurements were performed in three different points marked in Fig. 1 by triangles. The aim of this experiment was to determine, whether the increasing distance of Station B would impact the multirate capabilities of Station C, i.e., whether the transmission from the server to Station A would be influenced.

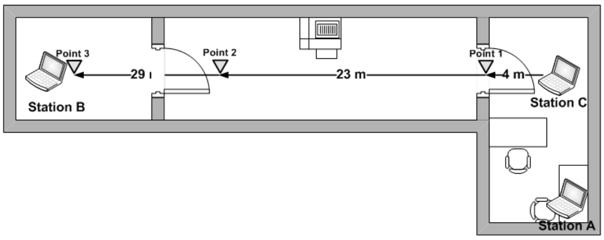

Fig. 1. Testbed

All possible sources of interference in the 2.4 GHz and 5 GHz bands (e.g., access points or Bluetooth devices) were eliminated for all experiments.

5 Measurement Results

From all the acquired results, we have decided to present two case scenarios, which serve as an illustration for certain important findings. It is important to keep in mind that since the clients were downloading data from the FTP server, the vast majority of the analyzed data are the DATA frames sent by the server and the ACK frames it received in return. Therefore, the results show how the server behaved (in terms of rate selection) when simultaneously communicating with two clients.

The first scenario consisted of a Lucent server (i.e., Station C was using a Lucent card, c.f. Fig. 1) and two Linksys clients (Stations A and B) communicating in the 802.11b standard. The results are presented in the form of graphs in Fig. 2 and Fig. 3. The first graph shows the percentage of all frames at a given measurement point, the second graph – the percentage of all data.

In Fig. 2 it can be clearly seen that while Station A (the stationary one) received a constant rate of 11 Mbps for its DATA frames, Station B's transmission rate dropped successively the further it was from the server.

Fig. 3 is a demonstration that, in terms of actual bytes sent, the overall share of the ACK frames is extremely small when compared to the DATA frames. Therefore, it would be impossible to observe the rate changes of ACK frames in this figure.

The second scenario proved to be more complex in terms of the data rates used. The server used a Proxim card, the stationary client – a Linksys card, and the moving client – a Proxim card as well. The results are shown in Fig. 4 and Fig. 5 (for the percentage of all frames and all data, respectively). The cards were operating in the 802.11g standard, which allows for a wide range of transmission rates (up to 54 Mbps). The first observation from the presented figures is that the Proxim card present at the server was using the basic rate (1 Mbps) to send its DATA frames to the Linksys client. This occurred despite the fact that the Linksys card was returning ACK frames in multiple rates (up to 11 Mbps). The reason for this is most likely vendor incompatibility. On the other hand, the Proxim client established a high speed link with the Proxim server. Both the DATA and ACK frames were able to utilize the potential of multiple transmission rates. At the first measurement point, the majority of DATA frames were sent with the highest available speed (54 Mbps), whereas all the ACK frames were sent at a speed of 24 Mbps. In the third measurement point up to 8 different rates were used (depending on radio conditions).

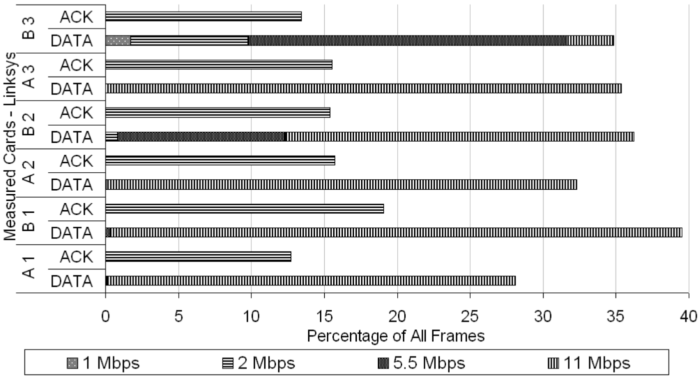

Fig. 2. Multirate performance of two Linksys cards (A and B) at three measurement points (1, 2, and 3): transmission speed vs. percentage of frames sent (at a given measurement point). The server was using a Lucent card

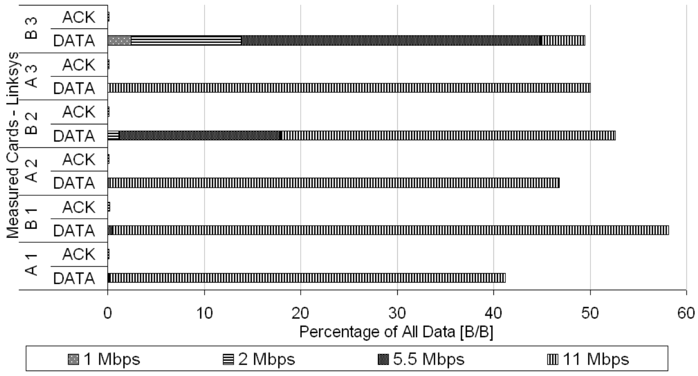

Fig. 3. Multirate performance of two Linksys cards (A and B) at three measurement points (1, 2, and 3): transmission speed vs. percentage of data sent (in bytes/bytes, at a given measurement point). The server was using a Lucent card

The fact that the Linksys card was transmitting at a rate of 1 Mbps means that it was underusing the channel and, therefore, degrading overall network performance. This is an example of how vendor incompatibility can lead to unfairness in the shared radio channel.

Comparing the two scenarios, we can see that in the first one (with 802.11b cards), the ACK frames were sent at a constant, basic rate of 2 Mbps. However, in the second scenario (with 802.11g cards) multiple rates were used. Based on these measurements it seems that in the 802.11b standard ACK frames are transmitted at a rate no large than 2 Mbps, whereas in 802.11g much higher rates can be used (up to 24 Mbps).

Furthermore, we can see that the rate of the mobile station does not impact the established rate of the stationary one. This means that near and far stations can coexist with multiple rates.

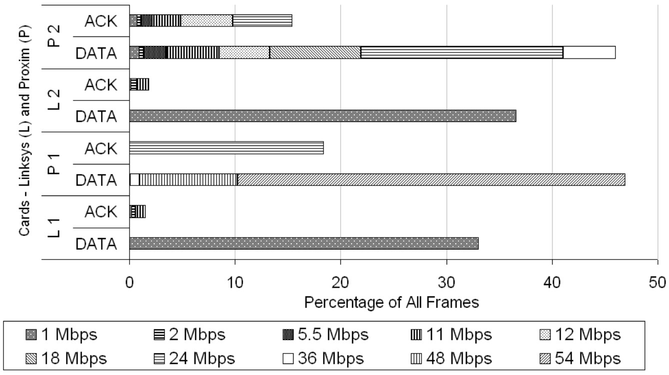

Fig. 4. Multirate performance of a Linksys (L) and Proxim (P) card at two measurement points (1 and 2): transmission speed vs. percentage of frames sent (at a given measurement point). The server was using a Proxim card

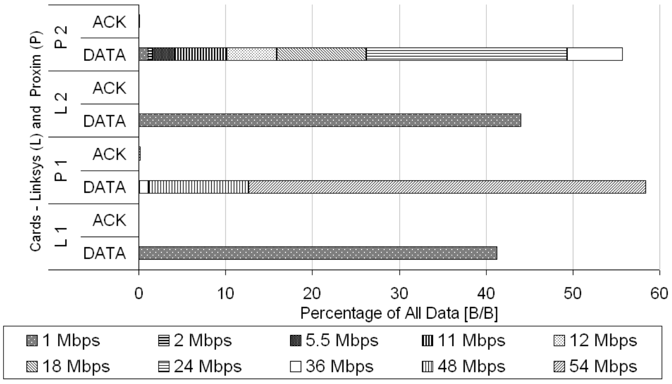

Fig. 5. Multirate performance of a Linksys (L) and Proxim (P) card at two measurement points (1 and 2): transmission speed vs. percentage of data sent (in bytes/bytes, at a given measurement point). The server was using a Proxim card.

6 Result Validation

In order to evaluate the obtained link layer throughput, we have compared them with theoretical values derived from the analytical model presented in Section 3. This comparison is presented in Table 2.

In order to take into account the use of multiple rates by the station, the theoretical value of the system throughput was calculated for each available rate and then summed up using a weighted average (based on bytes transmitted with a given rate). The DATA frame length *l* was taken as a weighted average of all transmitted DATA frames.

For the first scenario (Lucent server, Linksys clients), the measured results quite closely resemble the theoretical calculations. In this scenario, not many transmission rates were used and we believe this is the reason why the results are similar. This is also further validation of our mathematical model.

In the second case, however, the number of rates used was much larger and the difference between theoretical and measured values is quite significant. This is because our model did not take into account the procedures needed to change the rate and the impact of lost frames. This is why the measured values were much lower than the theoretical ones.

Table 2. Comparison of Theoretical and Achieved Throughput

Point	**FTP Server**	**Receiving Station**	**Throughput [Mbps]**		**Difference [%]**
			Theoretical	*Measured*	
1	Lucent	Linksys A	4.99	5.16	3.4
	Lucent	Linksys B	4.96	5.03	1.4
2	Lucent	Linksys A	4.97	4.72	0.75
	Lucent	Linksys B	4.15	3.80	8.4
3	Lucent	Linksys A	5.01	4.11	17.96
	Lucent	Linksys B	2.35	2.35	0
1	Proxim	Linksys	0.51	0.004	99.2
	Proxim	Proxim	21.64	3.66	83.1
2	Proxim	Linksys	0.51	0.005	99.0
	Proxim	Proxim	9.13	1.95	78.6

7 Conclusions

The behavior of IEEE 802.11b/g cards in multirate ad-hoc environments has been presented in this paper. Certain popular and widely available WLAN cards from different vendors were tested in terms of throughput and interoperability. Both the measurements and analytical results were compared.

The following general conclusions can be formulated. First of all, the obtained results show the inefficiency of multirate algorithms used in commercial cards. Secondly, it can be observed that cards of the same model from one vendor co-operate much better. If the number of used rates grows significantly (which is possible for 802.11g), the achieved throughput drastically decreases. This is because cards spend time adjusting to the channel conditions by trying to find the appropriate rate.

The differences between the ideal, theoretical and measured results (as exemplified in the second scenario) can be 1000-fold. Therefore, there is a strong need to develop new, efficient multirate algorithms. Most importantly, adequate agreements between different vendors are required to improve the co-operation of WLAN devices, especially since multirate IEEE 802.11b/g combo cards dominate the market.

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