

Practical analysis of IEEE 802.11b/g cards in multirate ad hoc mode

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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. 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. The achieved results, presented in the form of figures, show that cards manufactured by independent vendors perform differently. Therefore, choosing the optimum configuration, according to the user's requirements, is possible.

Keywords— *ad hoc, IEEE 802.11b/g cards, measurements, multirate.*

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 [1], 802.11a [2], 802.11b [3], and 802.11g [4]. 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 test-beds and radio conditions, but also because of vendor implementations.

A good example of this problem can be found in [5], where several IEEE 802.11 cards from different vendors were analyzed. The stress was on medium access control (MAC) implementations and hardware delays. Two meaningful conclusions appeared. First of all, it was shown that a notable unfairness in rate selection was present 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. One server was sending file transfer protocol (FTP) traffic to two clients.

The rest of the paper is organized as follows. The state of the art is presented in Section 2. A mathematical model for calculating transmission rates in IEEE 802.11 is described in Section 3. The measurement scenarios and results are shown in Sections 4 and 5, respectively. Section 6 gives a validation of the achieved results. Section 7 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 possible schemes of choosing the appropriate rate and it is up to the card vendors to decide which one to use.

The cooperation 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 IEEE 802.11b and IEEE 802.11g cooperation.

It must also be noted that transmission rates are not linear. Therefore, e.g., an 11 Mbit/s link with a delivery ratio of just above 50% always outperforms a 5 Mbit/s link.

Table 1
Comparison of preamble, header, and payload rates

Mode (lp/sp: long/short preamble)	Physical layer convergence procedure (PLCP)		Payload [Mbit/s]
	preamble [Mbit/s]	header [Mbit/s]	
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

Multirate algorithms can be based on statistics. The auto rate fallback (ARF) [6] protocol is perhaps the first multirate algorithm developed and one of the most commonly used. To determine the channel quality, ARF utilizes link layer acknowledgement (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 IEEE 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 [7], adaptive multi rate retry (AMRR) [8], and SampleRate [9]. 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 signal-to-noise ratio (SNR)-based algorithms such as receiver based auto rate (RBAR) [10]. In this solution, the receiver measures the SNR value of the received request to send (RTS) and uses the clear to send (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 opportunistic auto rate (OAR) protocol [11]. It utilizes the coherence times of good channel conditions to send high-rate multi-frame bursts. This is similar to the transmission opportunity (TXOP) feature of IEEE 802.11e [12]. 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 IEEE 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 [5] (closely related to the work done in [13]). The authors measure the performance of six IEEE 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 IEEE 802.11b cards from different vendors [14]. Their results show high correlation between the modeled, sim-

ulated 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 throughput¹ of five different IEEE 802.11b access points (APs) can be found in [15]. 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 [16] and [17]. 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 (DATA) frame of length l to station j at time t . The basic assumptions are that data frames are of equal length, there are no hidden stations and all data frame transmissions are 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 base station system (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 the propagation delay, S is the overall system throughput, T_S (or T_C) is expected time interval between periods when the channel is idle for a distributed inter-frame space (DIFS) period, within which at least one successful (or collided) transmission took place.

A successful transmission must fulfill the following three conditions. Firstly, the sender and the receiver stations are not hidden from each other. Secondly, no other station being within the range of the receiver starts its transmission within the time period $[t - \beta, t + \beta]$. Finally, 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, the 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 $G = \sum_{i,j} G(i, j)$.

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

A simple observation shows that:

$$T_C \geq \frac{1}{G} + l + DIFS + \beta, \quad (1)$$

$$T_S = \frac{1}{G} + l + SIFS + l_{ACK} + DIFS + \beta, \quad (2)$$

where $\frac{1}{G}$ is the expected time until the beginning of a transmission of the first frame after the channel was sensed idle for DIFS, and SIFS is short inter-frame space.

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 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:

$$p_s(i, j) = e^{-N(N-1)\lambda\beta}. \quad (3)$$

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 $\frac{G(m, n)}{G} (1 - e^{-\beta G(i, j)})$.

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

$$\begin{aligned} S(i, j) &\approx \frac{p_s(i, j) \frac{G(i, j)}{G} + p_s(i, j) (1 - e^{-\beta G(i, j)}) \sum_{(m, n)} \frac{G(m, n)}{G}}{T_S} \\ &= \frac{p_s(i, j) \frac{1}{N(N-1)} + p_s(i, j) (1 - e^{-\beta\lambda}) \frac{N(N-1)-1}{N(N-1)}}{\frac{1}{G} + l + SIFS + l_{ACK} + DIFS + \beta}. \end{aligned} \quad (4)$$

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

$$\begin{aligned} S &= N(N-1) \frac{p_s(i, j) \frac{1}{N(N-1)} + p_s(i, j) (1 - e^{-\beta\lambda}) \frac{N(N-1)-1}{N(N-1)}}{\frac{1}{G} + l + SIFS + l_{ACK} + DIFS + \beta} \\ &= \frac{p_s(i, j) + p_s(i, j) (1 - e^{-\beta\lambda}) N(N-1) - 1}{\frac{1}{G} + l + SIFS + l_{ACK} + DIFS + \beta}. \end{aligned} \quad (5)$$

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 30 mW. The card vendors do not provide information on the type of multirate algorithms used.

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

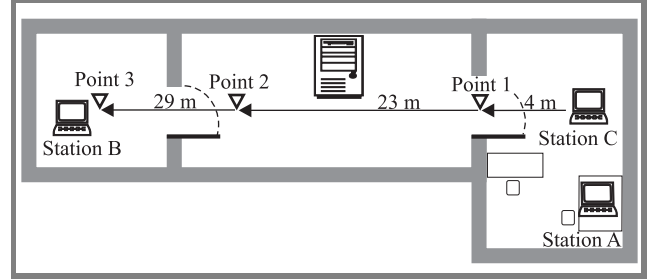


Fig. 1. Test-bed.

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 the 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.

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 six 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 the two clients.

The first, the second and the third scenarios are presented in Figs. 2–4, respectively. They show the percentage of DATA and ACK frames received/sent by the clients from/to the server during the whole experiment. As can be seen in the figures, three different measurement points are considered. In all of the three scenarios the stations were communicating with the use of the IEEE 802.11b standard. In terms of actual bytes sent, the overall share of the ACK frames is of course extremely small compared to the DATA frames.

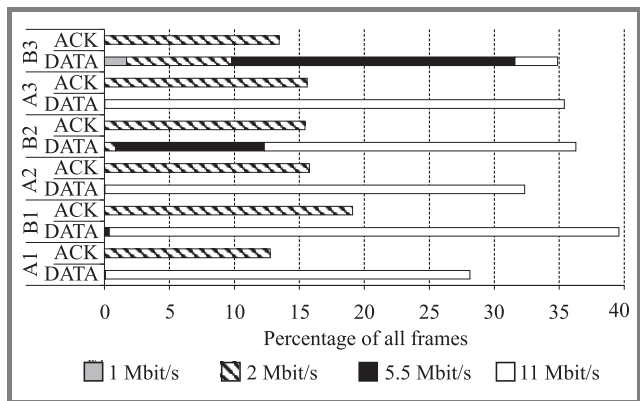


Fig. 2. Multirate performance of two Linksys cards (A and B) at three measurement points (1, 2, and 3): transmission speed versus percentage of frames sent (at a given measurement point). The server was using a Lucent card.

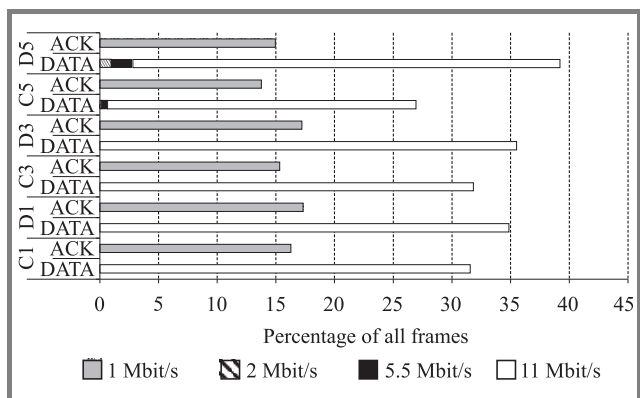


Fig. 3. Multirate performance of a Cisco 350 (C) and a DLink (D) card at three measurement points (1, 3, and 5): transmission speed versus percentage of frames sent (at a given measurement point). The server was using a Cisco 350 card.

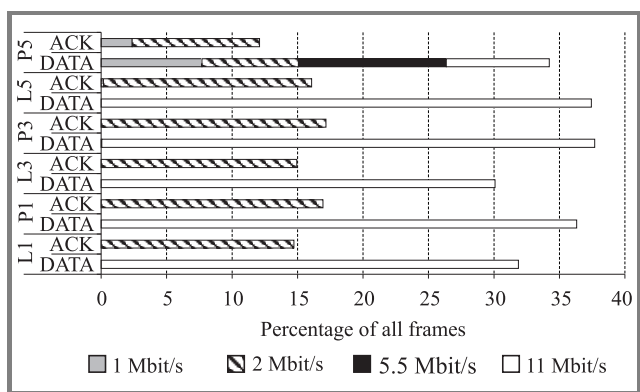


Fig. 4. Multirate performance of a Proxim (P) and a Linksys (L) card at three measurement points (1, 3, and 5): transmission speed versus percentage of frames sent (at a given measurement point). The server was using a 3Com card.

The first scenario consisted of a Lucent server and two Linksys clients (stationary – A, moving – B, see Fig. 2). The second scenario consisted of a Cisco 350 server and two clients (Cisco 350 – stationary, DLink – moving,

see Fig. 3). The third scenario consisted of a 3Com server and two clients (Linksys – stationary, and Proxim – moving, see Fig. 4). In all cases, practically all the time, the servers were sending their DATA frames to stationary clients at a constant rate of 11 Mbit/s (independently of the measurement point). Whenever their transmission rates dropped, they dropped to 5.5 Mbit/s. Such a situation did not happen often, i.e., almost all frames were sent at the highest possible rate. For the moving stations, however, the servers’ transmission rates dropped the further the clients were away from the servers. The worst performance of a moving station was observed in the first case, slightly better for the third case and the best for the second case. Therefore, it can be concluded that at long distances it is hard for a Linksys client card to communicate with a Lucent server card. Additionally, the Proxim client can communicate with the 3Com card, though, at long distances its transmission speed drops. The most satisfying conclusion is that a DLink client can communicate flawlessly with a Cisco 350 server even at long distances. In the view of ACKs for both stationary and moving clients, in the second scenario the cards were sending ACKs with a lower transmission rate (i.e., 1 Mbit/s) than in the first (i.e., 2 Mbit/s) and the third scenario (i.e., generally 2 Mbit/s but also 1 Mbit/s at long distances).

In the second set of measurement scenarios (fourth to sixth) the cards were operating in the IEEE 802.11g standard, which allows for a wide range of transmission rates (up to 54 Mbit/s). These scenarios proved to be more complex in terms of the data rates used.

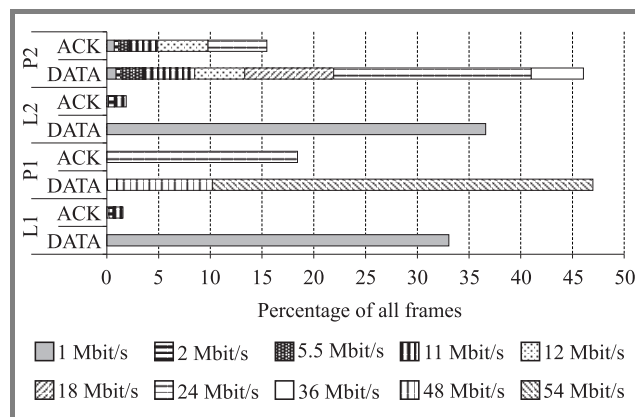


Fig. 5. Multirate performance of a Linksys (L) and Proxim (P) card at two measurement points (1 and 2): transmission speed versus percentage of frames sent (at a given measurement point). The server was using a Proxim card.

In the fourth scenario, 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. 5. The first observation from the presented figure is that the Proxim card present at the server was using the basic rate (1 Mbit/s) 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 Mbit/s).

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 Mbit/s), whereas all the ACK frames were sent at 24 Mbit/s. In the third measurement point up to 8 different rates were used (depending on radio conditions). The fact that the Linksys card was transmitting at 1 Mbit/s 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.

The next scenario (Fig. 6) had a similar configuration as the previous one. The only difference was that the stationary client was using a Lucent card. This time the co-operation between different cards was somewhat better. The server was sending data at 11 Mbit/s to the Lucent client. The client was responding with ACK frames sent in multiple rates up to 11 Mbit/s. This result is better than in the previous scenario where only 1 Mbit/s was achieved. However, the communication between Proxim cards was better because they made use of the full range of possible rates.

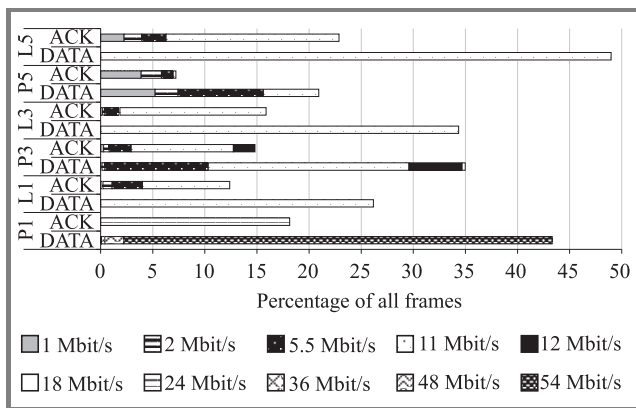


Fig. 6. Multirate performance of a Lucent (L) and a Proxim (P) card at three measurement points (1, 3, and 5): transmission speed versus percentage of frames sent (at a given measurement point). The server was using a Proxim card.

The behavior described above was present in the final scenario (Fig. 7) in which the stationary client's card was a Cisco card. The only difference was that the Proxim server managed to send not only 11 Mbit/s frames but also a small number of 12 Mbit/s frames to the Cisco client. The stationary client responded with ACK frames in multiple rates (up to 11 Mbit/s).

The main conclusion from these three scenarios operating in the IEEE 802.11g standard is that the Proxim card had severe problems with establishing a high rate connection with cards from other vendors. No two cases were the same, with the maximum rate used being 1, 11 and 12 Mbit/s. However, all of the non-Proxim clients sent ACK frames

at a rate of 11 Mbit/s (or less) and the Proxim client used a maximum of 24 Mbit/s. The exact reason of this behavior is of course unknown as we do not know how the cards chose to adapt their rate.

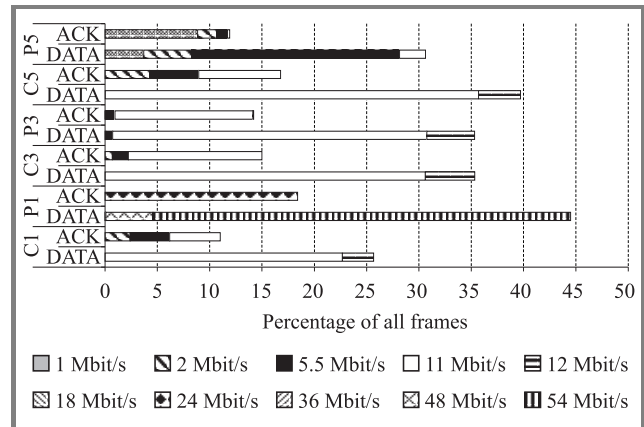


Fig. 7. Multirate performance of a Cisco (C) and a Proxim (P) card at three measurement points (1, 3, and 5): transmission speed versus percentage of frames sent (at a given measurement point). The server was using a Proxim card.

Comparing the scenarios operating in the 802.11b and 802.11g standards, we can see that in the first ones the ACK frames were sent at basic rates of either 1 Mbit/s or 2 Mbit/s. However, in the second set of scenarios multiple rates were used. Based on these measurements it seems that in the IEEE 802.11b standard ACK frames are transmitted at a rate no larger than 2 Mbit/s, whereas in 802.11g much higher rates can be used (up to 24 Mbit/s). 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.

6. Result validation

In order to evaluate the obtained link layer throughput, we have compared two scenarios (first and fourth) 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 at a given rate). The DATA frame length l was taken as the 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 a further validation of our mathematical model.

In the fourth scenario, however, the number of rates used was much larger and the difference between the theoretical and the measured values is quite significant. This is because

Table 2
Comparison of theoretical and achieved throughput

Point	FTP server	Receiving station	Throughput [Mbit/s]		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

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.

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 obtained results show, that the performance of a WLAN card highly depends on its manufacturer. Some cards turned out to be significantly worse than others, because they implement the multirate functionality differently. Furthermore, the authors are convinced that the sensitivity of the cards also had a significant impact on the correct reception of packets.

Therefore, to achieve high performance, it is crucial to implement an appropriate algorithm which can choose the best transmission rate. If the rate is chosen too high, the frame error rate increases which leads to more retransmissions and, as a consequence, network performance decreases. If the card is not able to quickly adapt to varying radio channel conditions or if it chooses a rate which is too low, the degradation of network performance will also occur. Thus, high adaptability with the utilization of short periods of good conditions seems to be a good solution.

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 cooperate much better. If the number of used rates grows significantly (which is possible for IEEE 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. Finally, perhaps the rate used to send the ACK frames should suggest to the sender of the DATA frames which rate to choose.

The differences between the ideal, theoretical and measured results (as exemplified in the fourth 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 cooperation of WLAN devices, especially since multirate IEEE 802.11b/g combo cards dominate the market.

When buying a WLAN card it is important to take into account the transmission rates but also other parameters (e.g., sensitivity, output power and laboratory tests). Therefore, to facilitate the user's final choice Table 3 was prepared and presented. It contains the comparison of subjective card compatibility. ProximG card is the winner since it reaches the best compatibility results. D-Link and Cisco cards are a little poorer. The Lucent and Linksys cards seem to be the worst choice considering the compatibility aspect.

Table 3
Comparison of subjective card compatibility

Cards	3Com	Proxim G	Lucent	Cisco 350	Average
Proxim G	2	1.75	—	—	1.88
Lucent G	1.5	1	—	—	1.25
Linksys	1	0	2	—	1.00
DLink	—	1	2	2	1.67
Cisco	2	1	—	2	1.67

Future research should provide more information about the problem of multirate adaptation and card behavior. The proposed mathematical model should be revised to be in line with experimental results. Furthermore, it is important to continue studying the problem of achieving multirate compatibility between cards belonging to different vendors.

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