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Row measurement traces are to be found on http://www.tkn.tu-berlin.de/traces/slowmotion/

Measuring the Impact of Slow User Motion on Packet Loss and Delay over IEEE 802.11b Wireless Links

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Abstract

IEEE 802.11b compliant WLAN technology is increasingly used for cordless telephone services. Often, a WLAN phone is moved during a call. In the present paper we explore to what extent slow user motion influences the wireless link quality. We conducted extensive measurements with speech over commercial WLAN equipment using an experimental environment enforcing controlled motion. Our experiments show that – in contrast to the common assumption – an increase of motion speed can result in a better link quality: The packet loss rate and variance, measured after link-layer retransmissions, decreases. In addition, our measurements demonstrate that the modulation type, the maximal number of retransmissions, the experimental setting, and even the quality of power supply are the dominant influences on link quality.

1. Introduction

The tremendous success and the wide spread use of Wireless LAN radio modems, based on the IEEE 802.11 standards [1], have come hand in hand with decreased costs of network cards and base stations [2]. Increasingly, WLAN is not only applied for the original purpose of its design, which is to connect wirelessly computers in local area networks, but also for special purpose devices. Hand-held palm computers, bar code scanners and cordless phones use IEEE 802.11 radio modem technology as well [3][4][5][6]. Especially WLAN phones are expected to have a larger market-share. On the one hand WLAN phones promise benefits, which are a converged, integrated communication network and low-cost Internet telephony. But on the other hand they suffer from high energy consumption and low range as compared to classic cordless phones based on DECT. Improving Voice over WLAN may bring significant benefits to its increasing number of users.

Concerning the transmission quality the requirements of WLAN phones are quite different from those of WLAN PCs. The dominant traffic consists of low-rate, real-time and interactive voice flows. The demand for bandwidth is small as compared to the abundance of transmission capacity. VoIP flows suffer from packet loss, packet delay and delay variation. Furthermore, cordless phones are subject to slow user motion that is not typical for notebook usage scenarios.

In the past years, many publications have been presented, which describe the WLAN link characteristics. To the best of our knowledge, neither measurement results exist on how user motion influences packet loss rates nor have precise measurements of the overall transmission delay been presented so far.

It is crucial to understand and to know the loss and delay of the wireless link, if communication protocols are to be developed, evaluated or implemented. An experimental set-up, which precisely measures the performance of Voice over WLAN, is an essential part to develop high-quality VoIP cordless phones for demonstration and production. In addition, a wireless channel model, which bases on real measurement results, is an important part in simulation models of networking systems.

This work presents measurements of packet transmissions over IEEE 802.11b. Between two nodes, a base station and a mobile node, equipped with Intersil's PRISM 2 reference-design WLAN cards, bidirectional VoIP flows are generated. We measure the packets' transmission success and delay with our extended device driver. We alter the location, speed, and direction of movement of the mobile node. Different channel modulation types (automatic, 1 and 11 MBit/s) and different numbers of maximal MAC layer retransmissions are considered. The measurements were conducted in both an office environment and in a large gymnasium.

We start the article by reviewing previously published WLAN performance studies in section 2. Section 3 describes the measurement software and hardware setup. In section 4, we present and discuss the measurement results. At the end, we summarize the paper and draw final a conclusions.

2. Related Work

2.1. Measurements

The performance of WLAN radio modems has been measured quite often, but the impact of motion is rather seldomly covered.

Nguyen and Katz published results on WLAN measurements in 1995 [7]. They studied the loss behavior of AT&T WaveLan, a popular in-building wireless interface. They applied a trace-based approach and showed that WaveLan transmissions experience an average packet error rate of 2 to 3 percent. The authors developed an error model to control simulation models. The simulation models showed a high correlation with experimental results of TCP throughput on WLAN.

Willig and Wolisz [8] conducted bit error measurements taken with an IEEE 802.11b-compliant MAC-less radio modem in an industrial environment. Some measurement traces included machinery, which moved. The author's results allow drawing some conclusions about the error characteristic of wireless links: A general observation is that mean bit error rates are time-variable over several orders of magnitude. Sometimes, long lasting consecutive packet losses occur. Such link outages should be taken into account by higher layers. Furthermore, the measurement data lead to the conclusion that some bit errors result not from link errors but from defective or error prone hardware.

The only published work on WLAN link quality with moving nodes is by Chen and Forement, 1995 [9]. They studied radio communication between vehicles. Two cars were driven through outdoor environments. Both cars communicated via a 900MHz, 2Mbit/s WaveLAN radio. The authors were primary interested in the transmission range, if the nodes are out-of-sight, if additional cars were placed intermediate and if the two nodes were moving. They did not notice an increased packet error rate, if the cars were moving.

2.2. Simulations

In 1998, Lee *et al.* published an analysis of the performance of an IEEE 802.11-like MAC protocol used over a Rayleigh fading channel [15]. He studied the packets' delay and error rate in respect to the user motion. The analysis used a wireless channel simulator, which is based on a time-correlated Rayleigh fading model as described by Jakes [16]. It calculates a signal-to-noise ratio (SNR) that varies over time. Depending on the current modulation scheme, the bit error rate can be derived from the SNR value. Using such wireless channel model, the author simulated an unidirectional transmission of packets between two nodes, using a reservation based MAC protocol. As error control, an immediate automatic-resend-request protocol (ARQ) is applied. Thus, if a packet transmission fails, it is retransmitted at the expense of an additional delay.

The author analyzed the transmission in respect to two quality-of-service (QoS) requirements: a maximal packet loss rate and a maximal transmission delay. In the author's simulation model for a speed of $f_d = 10Hz$ the packet loss rate drops to nearly zero. Also the delay bounded transmission benefits from the user's mobility.

One interesting aspect of the findings of Lee is the interaction between wireless channel, physical layer and MAC protocol. However, until now they did not continue their simulation nor their results were verified or confirmed.

2.3. Analytic Studies

Zorzi achieved remarkable analytical results on the performance of packet transmission over mobile radio channels. In his early work Zorzi *et al.* [17] analyzed the accuracy of a two state Markov model, if it is applied as an approximation on block transmission over a slowly fading wireless channel (Jakes Rayleigh fading model). The Markov model describes a wireless channel with two states, good and bad. The states have exponential distributed hold times. The hold times decrease if the Doppler Frequency increases. Zorzi states that the Markov model is a good approximation; he applied it in his following publications.

For example, in [18] the authors analysed the lateness probability of an ARQ scheme on a two-state Markov channel. One result states that the propability of a packet being too late – even after queuing and multiple retransmissions – depends on the length of the error burst. For an average error burst length some what smaller than the packet length, the lateness probability is minimal. For longer and shorter burst lengths, it increases.

Even though Zorzi's analytical models can be applied widely, we did not find a study on the effects of slow user movements on IEEE 802.11b wireless links.

3. Measurement Setup

When the link characteristic for Internet Telephony is being studied, it is important to construct usage scenarios, which are similar to how humans conduct telephone calls with cordless phone. The usage of a cordless phone is often limited to a small area, e.g. a room or a building. Cordless phone technology like DECT allows for handovers between different base stations, but because of the large coverage of cordless phone technologies such a handover occurs rather seldom. The coverage of WLAN is much lower than DECT and therefore WLAN phones are more likely to conduct handover between different base stations. However, in this paper we limited our study to the no-handover case. Instead, we were interested in the effect of human movements, which are rather slow (e.g. 1 m/s). One should note that cellular phones are subjected to much faster motions (e.g. if calls are conducted in cars or trains). Cordless phones instead, cannot be used at that high decree of motion, because the coverage is not ubiquitous.

One important requirement is that the measurement results are to some extent reproducible. Even though a wireless link has a random and chaotic nature caused by many factors that influence the link quality, it should be possible to reproduce similar measurement campaigns. Furthermore, because of the high variability of wireless links, the measurements should last long enough to increase the statistical accuracy of the results. It is clear, that humans cannot be used to move the client, if both the measurement should be reproducible and last for some hours. Therefore, a mechanical *node mover* had to be constructed.

In the following, we describe the measurement set-up in a top down approach. The accuracy of description is chosen in such a way that it is possible to repeat same or similar experiments.

During all measurements a *simulated telephone call* between two participants was generated (Figure 1). The data flows are voice flows (RTP) in each direction, without any falsification by signaling traffic (e.g. RTCP, SIP or H.323). The traffic is carried between one *stationary PC* (referred as the base station) and the *mobile PC* (WLAN phone) over IEEE 802.11b. We suppressed any other data traffic from these PCs or third sources and switched off any interference source on adjacent frequencies. A node mover moved the WLAN phone regularly on fixed rails during some of the experiments. For example, we placed the WLAN phone at a distance of 8m and 12m. Subsequently, the node mover moved the notebook between both positions to study the impact of motion (8-12m).

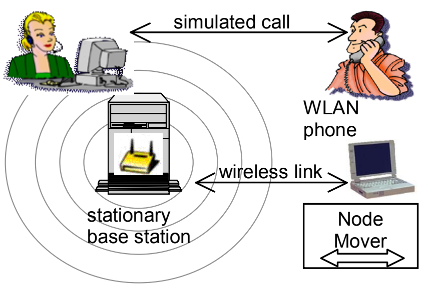


Figure 1. Scenario

Both PCs were running a Suse 6.4 Linux system with a 2.4.17 Linux kernel. On both PCs we measured packet transmission success and delay. To gather this data, we set up a measurement environment covering multiple components (Figure 2). During measurement a ping program on the stationary PC generates VoIP-like flows.

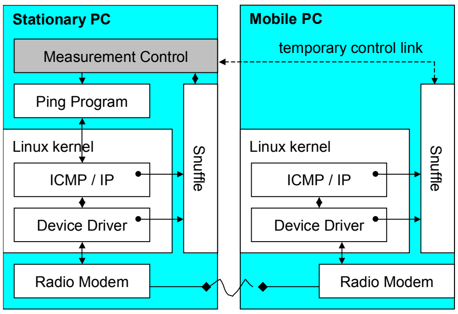


Figure 2: Measurement software

A modified WLAN device driver controls the radio modem. The radio modem implements the physical and MAC-layer part of IEEE 802.11b. Our measurement software Snuffle collected messages and protocol states from ICMP, the device driver and the radio modem on both PCs. Before and after each measurement we set up a temporary SSH secure shell link between both PC's over the wireless link to control the measurement and collect trace data.

3.1. VoIP Traffic Generator

A VoIP stream consists of a bidirectional flow of packets, which contain the audio data. To simulate such traffic pattern, we used the "ping" program. The stationary host generates ICMP echo request messages, which the mobile PC answers with an ICMP echo reply.[1] The mobile PC echoes a message of the same size and same IP Type Of Service (TOS) field as the received message. We use the TOS field to alter the link layer transmission mode (section 3.3).

During the measurement the ping program transmitted each 20ms a packet with a length of 78 bytes (including IP headers). This packet size corresponds to a VoIP flow encoded at a rate of 8 kbit/s.

We changed a ping program to support command-line driven packet sizes, IP TOS values and packet generation intervals.

3.2. IEEE 802.11b Network Interface

The IEEE 802.11 MAC is based on Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA), which resembles a one-persistent medium access scheme with probabilistic delay. A comprehensive explanation of the MAC protocol can be found in [1]. The physical layer is based on Direct Sequence Spread Spectrum (DSSS) in the 2.4 GHz Band, whereas DBPSK, DQPSK, and CCK modulations are used to support raw data rates of 1, 2, 5.5, and 11 MBit/s.

[1] One should note that if the ICMP request message is lost, no ICMP answer message is sent, too.

For our measurements, we used the PCMCIA reference design of Intersil's Prism2 chipset, which is implemented by ZoomAir and D-Link cards. It was selected because the radio modems comply with the IEEE 802.11b specification. Furthermore, a detailed description of the medium-access-controller can be obtained from Intersil, which allows setting up different transmission configurations. There is viable public source driver support for the Linux Operation System present, which facilitated the setup of the measurement environment.

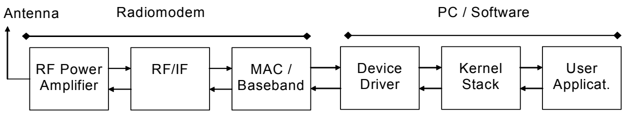


Figure 3. Schematic of a WLAN node

3.3. Device Driver

For WLAN cards based on Intersil's reference design three different open-source device drivers for the Linux OS are available. These are the WaveLAN, as it is included in the Linux kernel distribution, the Linux-WLAN project driver [10], supported by Intersil, and the Host AP driver [11]. For this work we chose the Host AP driver, version 2.5.2002, because at the time of decision it had most of the required features. We added measurement tracepoints to collect received and transmitted messages and radio-modem specific protocol states (section 0).

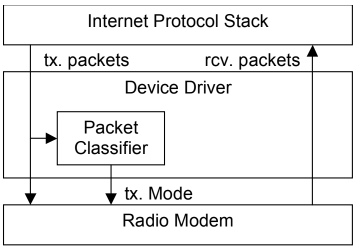


Figure 4. Packet classifier in device driver

Table 1. Flow-Specific Error Control

Packet Type	Modulation Type	Maximal no. of retransmissions
IPv4, ICMP, IP TOS=1	1 MBit/s	8
IPv4, ICMP, IP TOS=2	11 MBit/s	8
IPv4, ICMP, IP TOS=3	1 MBit/s	0
IPv4, ICMP, IP TOS=4	11 MBit/s	0
All other packets	Automatic	Automatic

We changed the device driver to support flow-specific link layer configurations [12], so that the error control is changed in according with the current flow classification (see Figure 4). Each packet in the device driver that is considered for transmission is analyzed with a packet classifier. The packet classifier looks at the packets' protocol headers. If a packet is identified as an IPv4 and ICMP packet, the error control is changed according to the table above.

3.4. Snuffle

To record the packets' transmission we applied our measurement tool Snuffle [13][14]. Snuffle consists of two components: a user-space program to collect and to store the measurement data and a kernel extension, which traces how packets traverse throughout the protocol stack. Compared to other measurement software, it can trace internal protocol states, too. Snuffle supports kernel trace points for TCP, UDP, ICMP, IP and IEEE 802.11b MAC protocols.

During the measurement campaigns, ICMP and IEEE 802.11b MAC packets were captured on both hosts. The captured data included the following fields (Table 2).

Table 2. Data value measured

ICMP tracepoint
Time stamp (µs), measured in the ICMP protocol
IP source and destination address
ICMP message type and code number
ICM echo ID and a sequence number
IEEE 802.11 transmit tracepoint
Time stamp (µs), measured in the device driver at the moment the packet is handled over from IP to the device driver.
Time stamp (µs), measured in the device driver's interrupt routine after the entire transmission process has finished.
IEEE 802.11 frame control field
1^{st}, 2^{nd}, 3^{rd} MAC address
MAC packet length
Success or failure of transmission
IEEE 802.11 receive tracepoint
Time stamp (µs), measured in the device driver in the interrupt routine after the entire transmission process has finished.
MAC Time stamp (µs), measured in the radio modem at the time receiving the packet.
RX status, which contains the message type, MAC mode, checksum errors, etcs.
Signal strength before receiving a packet and at the beginning of the receiving process.
Modulation type (1, 2, 5.5, and 11 MBit/s)
Frame control field (data or signaling frames)
Duration (µs) of RTS/CTS/Data and ACK sequence
1^{st}, 2^{nd}, 3^{rd} MAC address
MAC packet's sequence number
MAC packet length

3.5. Experimental Node Mover

Our experimental node mover is a large toy locomotive, which carries a notebook. The locomotive moves along over a curved rail or straight rail, which are both 5 m long. At the ends of the rail, the locomotive stops automatically and starts driving back the rails in the reverse direction. The maximum speed of the train is approximately 1 m/s. However, the relative speed between stationary PC station and mobile PC varies between 0 and 1 m/s, depending on the position and angle of the rails.

Figure 5. Node mover

To ensure power supply of the notebook even for long measurements it was inevitable to provide an external power supply because the capacity of the build-in batteries is not large enough. First, we connected the notebook with its power supply unit by a long cable. But this solution was not reliable because the cable had to be pulled behind the locomotive and sometimes got entangled with the rails.

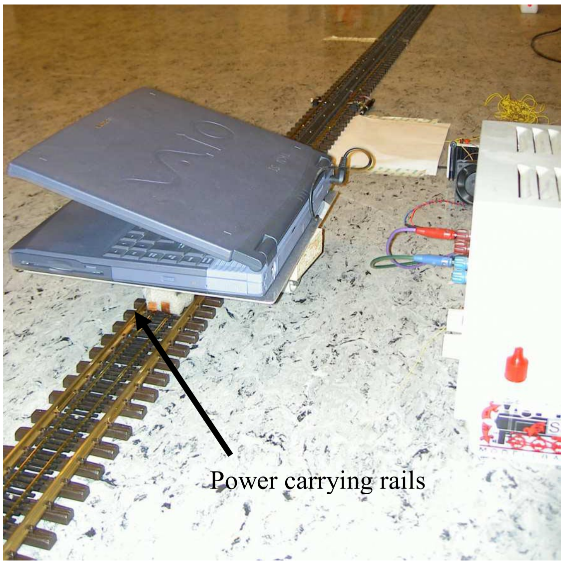


Figure 6. Power supply-setup

To overcome this shortcoming we used additional rails (Figure 6), which were placed between the primary rails. These rails were used as permanent power supply for the notebook. Two sliding contacts beneath the locomotive connected the notebook with the secondary rails (Figure 7).

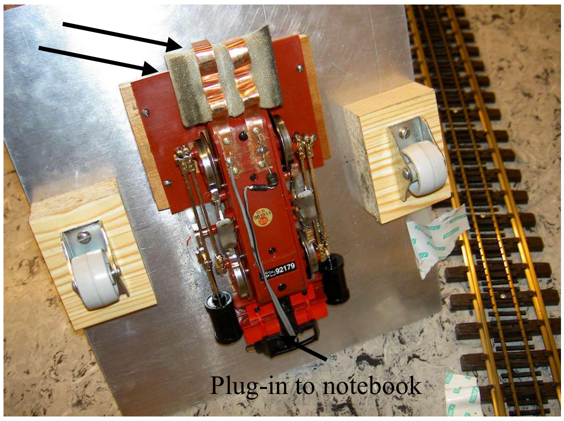


Figure 7. Sliding contacts for permanent power

3.6. Locations

To study dependence of the transmission quality on location, we placed the rails at three different positions within a ferroconcrete building. The first position was close to the stationary PC, in a range between 1 and 5m. Few errors are to be expected in that case. The second position had a distance between 8 and 12m. The third positions were at a critical distance (18-22m), because the link quality starts to get bad. A ferroconcrete wall was between positions 2 and 3 and the base station (Figure 8).

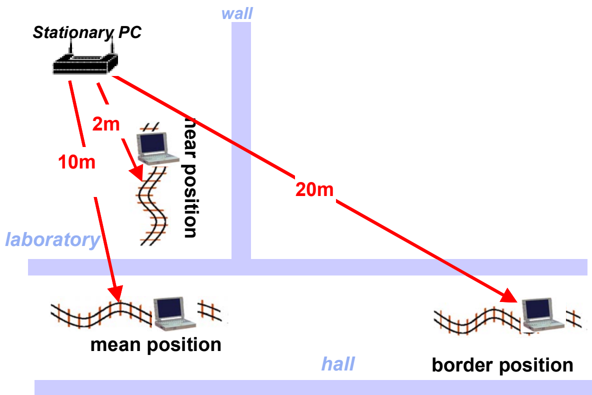


Figure 8. Measurement location (office)

In order to be independent from the impact of walls we did additional measurements in a gymnasium. In order to explore the influence of distance, speed and moving direction on the link quality (Figure 9), if the connection is line-of-sight.

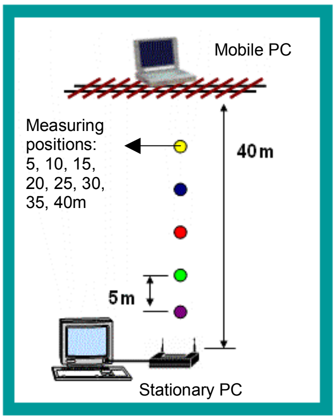


Figure 9. Measurement location (gym)

3.7. Analysis

Each measurement, which lasted several minutes to some hours, was divided into intervals of 128s, which is a length of a typical telephone call. For each telephone call we calculated the mean packet loss rate, which is the number of transmission failures as notified by the stationary PC. Transmission failures occur, if the stationary PC does not receive any immediate acknowledgement even after multiple retransmissions.

If the packet was transmitted successfully we subtracted the finishing time stamp from the starting time stamp. Both time stamps are measured on the stationary PC by the Snuffle tracepoints. The delay, being the difference between the time stamps, includes the queuing delay, the transmission duration of the packets (data und ack.) and the MAC access delay times the number of transmission attempts.

Because of the automatic selection of the modulation type and because of multiple transmissions attempts, this duration can vary to a large extent as we see in the forth-coming results.

3.8. Accuracy of time stamps

Time stamps are measured in an operating system, which has a measurement inaccuracy due to interrupt latencies and a lack of real time support. To figure out the interrupt latency, we measure the arrival times of packets. Every 20ms WLAN packets are received. The arrival times were measured at two positions: First, in the radio modem with a build-in clock. Next, at the interrupt handling routine in the operating system with the kernel call "gettimeofday". The clock in the radio modem is not subjected to jitter. Therefore, we used it as a reference clock. The radio modem clock and the operating system clock have a frequency offset of approximately 0.38%. For the following comparison we corrected both the frequency offset and an absolute offset. Then, for each received packet we calculated the difference between corrected radio modem time stamp and the OS time stamp. Figure 10 shows the distribution of these differences and thus the resolution of the OS clock. About 95% of all measurement values have an error of less than 0.2ms.

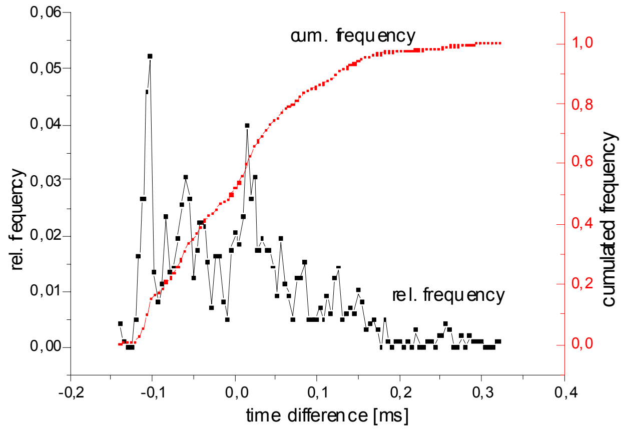


Figure 10. Difference between OS clock and radio modem clock

4. Results

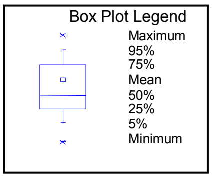
We started three measurement campaigns to identify the relation between motion and link quality. Starting from a black box approach using a vanilla radio modem configuration and measurement set-up, we tried to remove in the following campaign all obstructions towards a deeper understanding of the system behavior. In the following, we will describe the results obtained by these measurement campaigns.

4.1. Campaign 1: Office, Base Station Mode

We conducted our first measurements with the default configuration of the radio modem, which is an adaptive rate selection, DCF MAC mode, no fragmentation, maximal eight immediate MAC retransmissions, and no RTS/CTS. A stationary PC was configured as base station (master) whereas the mobile PC operated as client.

The adaptive rate selection automatically switches to the next lower modulation rate after transmission errors have occurred. The supported rates are 1, 2, 5.5, and 11 MBit/s. If the link is error free for some period of time, the modulation rate is increased again. The particular algorithm depends on the firmware implementation of the radio modem and is not standardized.

We conducted nine measurement series, each lasting one hour. The mobile node was placed at different positions, which were roughly 1,5,8,12,14 and 18m away from the stationary PC (Figure 8). Alternatively, we moved the mobile node at slow speed between two positions (e.g. between 1 and 5 meters). Figure 11 shows the packet loss rate as measured at the networking layer. The box plots take into account all telephone calls. They contain the mean, median, percentiles and extremes of the calls' loss rates.



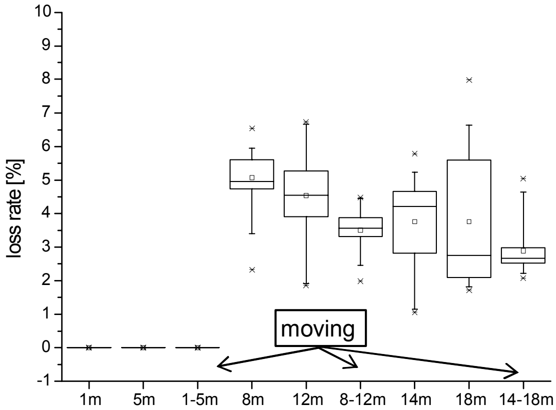


Figure 11. IP packet loss rate vs. position and motion, default radio configuration

We measured the delay (Figure 12) for each successfully transmitted packet. This delay includes queuing delay (if any), transmission delay of data packet and acknowledgement, scheduling delay and interrupt latency.

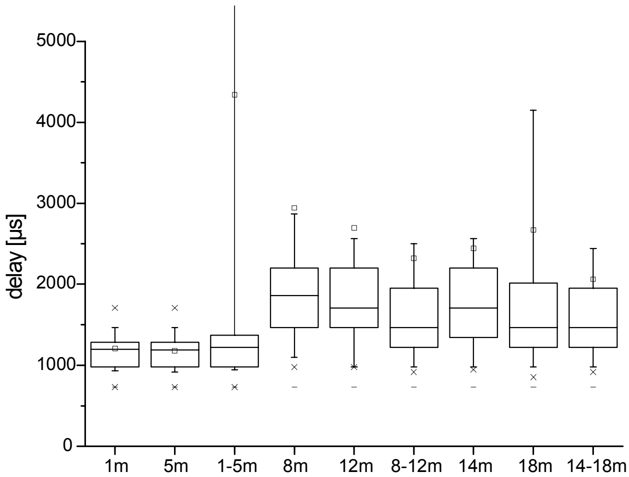


Figure 12. Packet delay versus position and motion, default radio configuration

If the distance between base station and node is small, no packet losses are visible at the networking layer. As the distance increases and a wall separates BS and client, the loss rates range between 2 and 5 %. The delay also increases. These measurement data suggest that if the client moves, the loss rate is slightly lower than in the stationary positions and the link quality is more stable and less variable.

To understand the transmission process of the MAC protocol we studied the delay distribution (Figure 13). Most packets (98%) are transmitted within 5ms. If we compare the delays of different distances, we see that the farer the node, the longer a transmission takes. This is understandable, because the radio modem selects a slower, physical modulation, as soon as the link quality gets worse. Furthermore, we can see that few packets are transmitted multiple times, if their transmission fails in the first attempt.

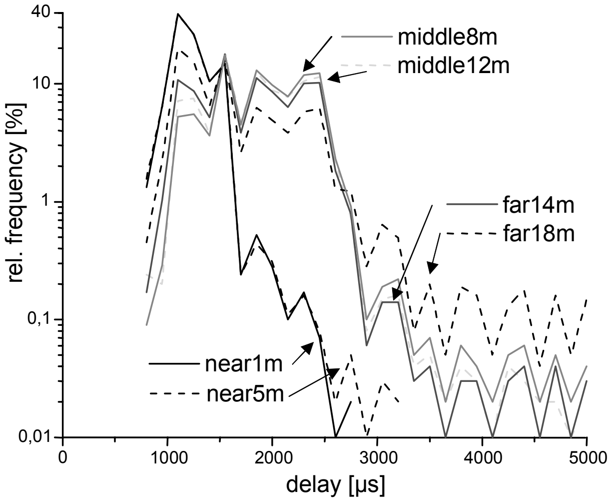


Figure 13. Histogram of transmission delays

In each measurement row, we found some very long lasting packet transmissions with a delay larger than 20ms (Figure 14). It is not clear which effect has caused this delay.

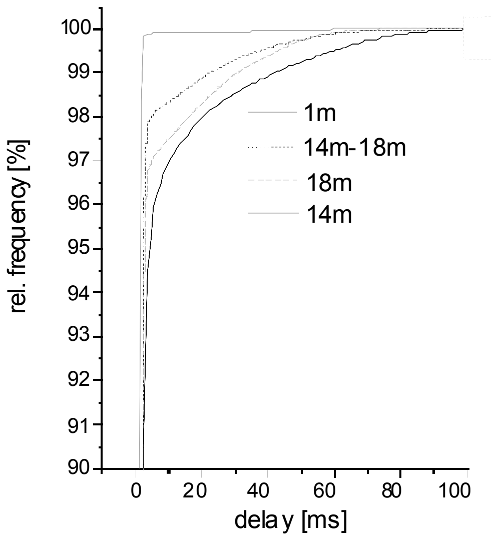


Figure 14. Cumulated distribution of delays

4.2. Campaign 2: Office, Ad-hoc Mode

The first campaign gave us an impression of the relation between motion and link quality. We wanted to get more information; therefore in the second campaign we changed the modulation type and the number of maximal link layer retransmissions (ARQ). The measurement setup was altered to allow longer measurements. The rails were straight and the mobile PC was power supplied by additional rails and not by a cable. At each position we measured for 75 minutes. We altered the link layer configuration and changed the modulation type (1, 11 MBit/s and automatic rate selection) and the number of maximal retransmission attempts (0 and 8). The results can be seen in Figure 15 and Table 3.

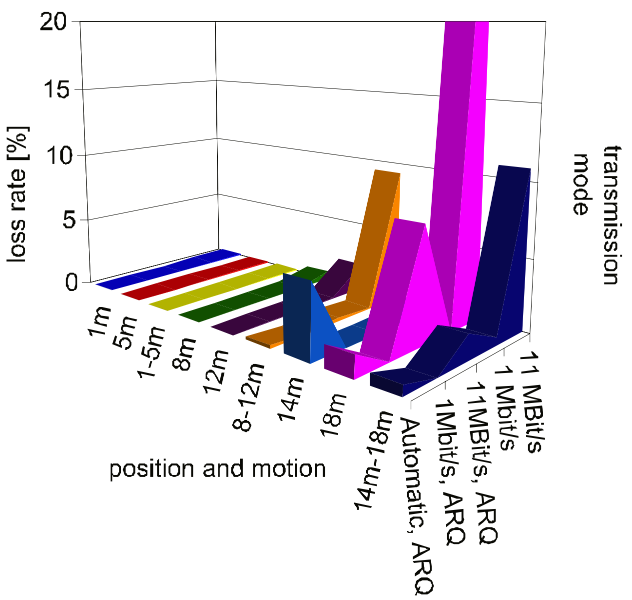


Figure 15. Loss rate vs. error control, position and motion

Table 3. Loss Rate (%) vs. Error Control, Position and Motion

Position	Autom., ARQ	1MBit/s, ARQ	11MBit/s ARQ	1 MBit/s, no ARQ	11MBit/s no ARQ
1m	0,00	0,00	0,00	0,05	0,03
5m	0,00	0,00	0,00	0,03	0,03
1-5m	0,00	0,00	0,00	0,05	0,11
8m	0,01	0,00	0,01	0,04	0,58
12m	0,00	0,00	0,00	0,03	1,84
8-12m	0,23	0,00	0,24	0,07	9,28
14m	5,11	0,00	0,00	0,06	0,37
18m	1,50	0,00	7,89	0,04	40,70
14-18m	0,75	0,00	1,73	0,52	10,83

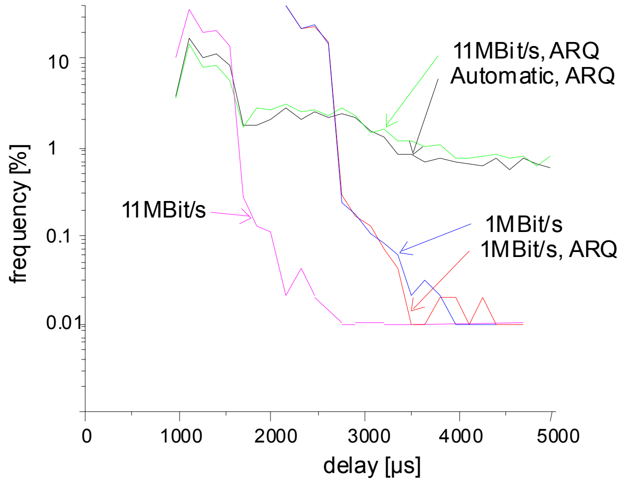


Figure 16. Delay histogram at position 18m

The transmission delay depends largely on the number of retransmissions and the modulation speed, as can be seen in Figure 16. In case of the 11 MBit/s and 1 MBit/s mode without ARQ most transmission delays are at 1.2ms and 2.4ms respectively. However, even in those cases some delays are higher because of a variable MAC access time and interrupt latency. The 1MBit/s mode with ARQ has a similar curve as the mode without ARQ, which leads to the conclusion that hardly any retransmission occurred. The frequencies for the automatic and the 11MBit/s (ARQ) modes are high for delays larger than 2ms, because of multiple retransmission attempts. One should note that between two transmission attempts a random, distributed backoff delay is chosen. This protocol behavior explains the smeared, steady curve that has only one peak at the beginning.

4.3. Campaign 3: Gymnasium

Because the second campaign did not provide any plausible relation between loss and motion, we changed the location and moved the equipment to a large, empty gymnasium in a grammar school. The measurement set-up is identical to the second campaign; however we altered the positions of the PCs.

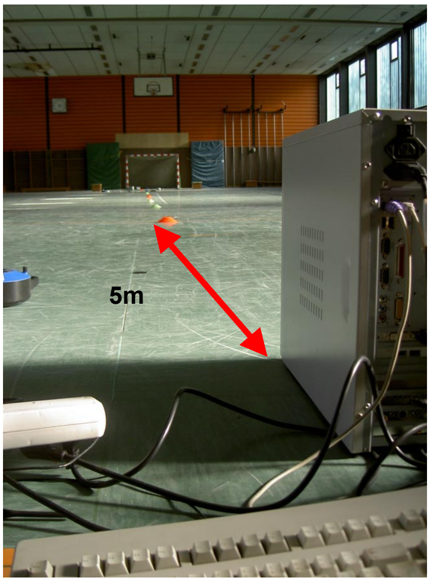


Figure 17. Measuring setup in the gym

4.3.1. Distance

First, we studied the impact of distance on the link quality. We measured loss rate and delay at each position for about 15 minutes. Figure 18 shows the packet loss rate versus the distance at the 11 MBit/s modulation, no ARQ. The transmission range in the empty hall is much wider than in the office environment. Even at 40m the link quality is quite good. However, at 5 and 15m we measure some high packet loss rates.

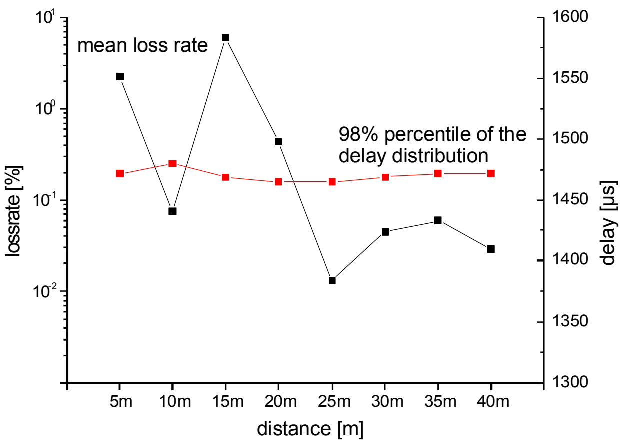


Figure 18. Gym: packet loss rate vs. distance, 11MBit/s, no ARQ

For all successfully transmitted packets, we calculated the 98% percentiles of delay (98% of all packets are as fast or faster). We considered only those 98% packets, because some transmission delays are so high (>20ms) that they falsified the results. As expected, the delay remains constant due to a fixed modulation scheme and only one transmission attempt.

4.3.2. Speed

Next, we measured the impact of motion speed on packet loss and delay. We altered the voltage of the toy train electrical supply so that the train drove at an average speed of 0.33, 0.5 and 0.65 m/s. The position of the mobile node was at 35m; the direction of motion is perpendicular to the main wave propagation. Figure 19 shows the loss rate and 98% percentiles of delay for both the 11 MBit/s mode with and without ARQ. If the node does not move at all, the loss rate is lower than during movement. The faster the mobile PC moves, the fewer retransmissions occur (Figure 19 and Figure 20).

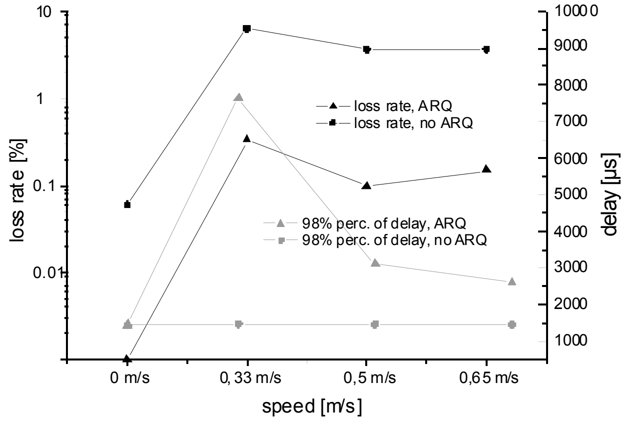


Figure 19. Gym: Loss and Delay vs. Motion Speed, 11MBit/s

The delay without ARQ is constant for all speeds whereas with ARQ being highest at 0.33 m/s and decreasing at higher speeds.

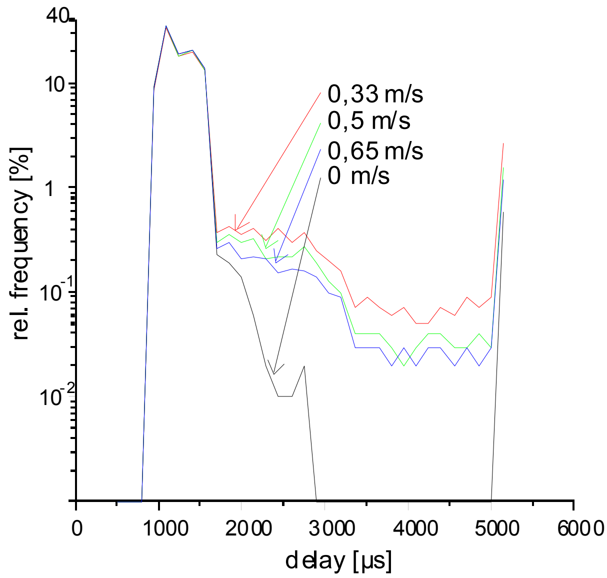


Figure 20. Delay histogram vs. motion speed, 11 MBit/s, ARQ

4.3.3. Direction

To see, whether the direction of movement and thus the speed relative to the base station has any influence, we changed the direction of the node's motion from perpendicular to parallel (to and away from the base station) and to a 45° cross direction Figure 21).

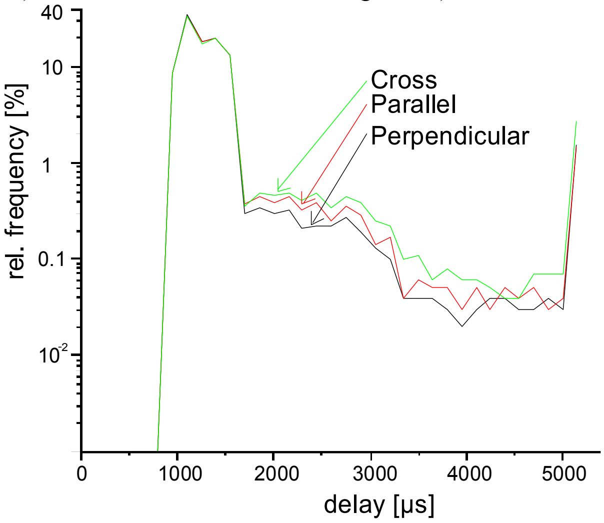


Figure 21. Delay histogram vs. motion direction. 11 MBit/s, ARQ

4.3.4. Power Supply

During movement of the mobile PC, the PC receives its power from secondary rails. Due to electromagnetic interference, due to a low quality power link or due to short interruption of the power supply, the radio modem may perform less well. For the perpendicular 30 to 35m measurement we conducted the same measurement once with normal power supply and once with battery power. During normal supply the mean packet loss mode in the 11 MBit/s mode was 5.2%. During battery supply it was 3.6%.

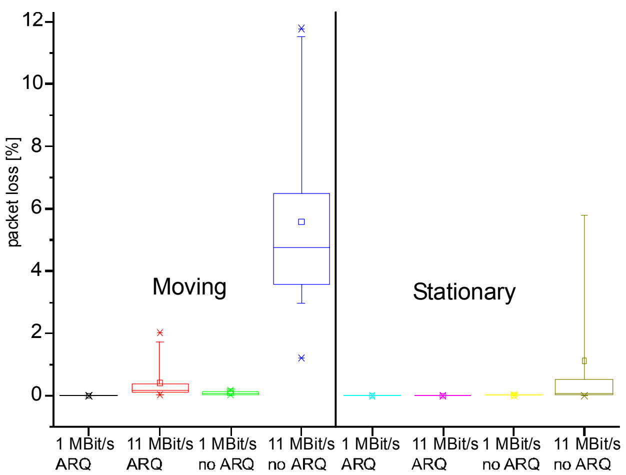


Figure 22. Gymnasium: Combined results

4.3.5. Overall

To increase the statistical accuracy we combined all measurement data, which were gathered in the gymnasium. We distinguished only between the link layer mode and the degree of movement (stationary or moving). Figure 22 shows that movement harms the link quality: The packet loss rate increases both before and after ARQ.

4.4. Summary

As the distance and the attenuation increase the packet loss rate increases too (Table 3). But even if the distance is short and line-of-sight, the link quality can be bad (Figure 18). As long as a wireless connection can be established, the packet loss rate after error control is mostly below 0.1%. Even in a "bad" position the loss rate seldom exceeds 5%.

The packet loss rate depends on the modulation type and the number of retransmission. 1MBit/s is, as expected, more reliable than 11 MBit/s. The 1MBit/s mode does not require many retransmissions.

For a fixed packet size and no background traffic, the transmission delay depends on the modulation type and the number of retransmissions. As expected, the transmission delay increases if ARQ is switched on. Measuring the transmission delay also gives an indication of the transmission mode used and current link quality.

During movement, however, if power is supplied over the secondary rails, the link quality is worse than using the batteries. This effect influenced strongly the measurement results of the second and third campaign. Thus, having an undisturbed power supply is essential.

Movements in the gymnasium worsen the link quality and the loss rate increases. The motion in the office environment has – at least in some measurements – a positive effect on the link quality (Figure 11). Both loss rate and delay were reduced and the link quality was more stable. The effect was more notable in the office environment, if the client and BS were separated by walls. In that case, multiple waves propagate on different paths causing interferences and a Rayleigh fading channel. Also, the positive effect of movement has only been seen if the automatic rate selection was active.

5. Conclusion

In this paper, we describe an experimental set-up and methodology for the measurement of the performance of an IEEE 802.11b compliant radio modem. The applied software (Snuffle) is able to trace protocol messages and states on multiple layers and nodes. Using this software; we were able to measure the packet loss and delay of IEEE 802.11b WLAN link using commercial radio modem cards.

Concluding, we can say that the factors, which are more important than the motion speed, are the modulation type, the number of retransmission, the attenuation, the environmental setting and the quality of power supply. The link quality of real wireless systems depends on many different factors, which are hard to control.

Continually improving the measurement setup we are conducting additional WLAN measurements. For example, our current experiments include analysis tools, which calculate the perceptual speech- and telephone-quality (e.g. ITU P.862 PESQ and the ITU G.107 E-Model).

We are also studying the impact of slow-user motion analytically [19]. The results show that the impact of frequency shifts is far too low to have a negative impact compared with the frequency instability of the clock.

Regarding the Rayleigh fading we can demonstrate that as the Doppler Frequency increases, the probability of the packet transmission failures increases, too. However, if the channel is in a bad state, the time, until the channel improves again, decreases as the Doppler frequency increases. Overall, slow fading worsens the link quality. We continue our studies to analyze, whether automatic rate selection benefits from a variable wireless channel.

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