An Empirical Evaluation of the Received Signal Strength Indicator for fixed outdoor 802.11 links

Michael Rademacher
Hochschule Bonn-Rhein-Sieg
Sankt Augustin, Germany
michael.rademacher@h-brs.de

Prof. Dr. Karl Jonas
Hochschule Bonn-Rhein-Sieg
Sankt Augustin, Germany
karl.jonas@h-brs.de

Markus Kessel
Hochschule Bonn-Rhein-Sieg
Sankt Augustin, Germany
markus.kessel@inf.h-brs.de

***Abstract*—For the evaluation of the received signal strength indication (RSSI) a different methodology compared to previous publications is introduced in this paper by exploiting a spectral scan feature of recent Qualcomm Atheros WiFi NICs. This method is compared to driver reports and to an industrial grade spectrum analyzer. During the conducted outdoor experiments a decreased scattering of the RSSI compared to previous publications is observed. By applying well-known mathematical tests for normality it is possible to show that the RSSI does not follow a normal distribution in a line-of-sight outdoor environment. The evaluated spectral scan features offers additional possibilities to develop interference classifiers which is an important step for frequency allocation in long-distance 802.11 networks.**

I. Introduction and Motivation

Our goal is the optimization of transmission quality in IEEE 802.11 long-distance wireless meshed networks (WiLD). One aspect in the optimization is the strength of the received signal. With respect to signal reception a strong signal is obviously better than a weak signal (and allows for higher modulation schemes resulting in higher data rates).

The value to work with on the receiving station is not the real received signal strength (RSS) but a RSSI provided by the driver of the NIC that takes local amplification (by the antenna), attenuation (by the cable) and other characteristics (receiver sensitivity) into account. Important for us is that *possibly*

- the RSSI can be used to determine the optimal modulation on that particular link;
- in combination with other parameters the RSSI can be used to indicate the distance between sender and receiver;
- *variations* in the RSSI can be indicators for interference.

Hence, understanding the RSSI is a first step towards optimal frequency allocation[1].

In a real world the RSSI will not be constant, even in an almost optimal (stable) environment. Therefor it is necessary to understand the expected *distribution* of the RSSI in order to identify deviations from it.

We want to understand the following aspects of the RSSI:

- What is the variation of these values, considering a stable short-term[2] environment?
- Is there an impact of the chipset, production series and driver.
- Is the overall accuracy comparable to industrial grade measurement tools?
- How many samples are necessary to consider in order to determine the "real" RSSI with a given probability?

Several authors have presented approaches for *modeling* the path loss in large-scale 802.11 outdoor networks [1] [2]. However, their evaluation of different propagation models does not take inaccuracies of the measured RSSI into account. This work will focus on an empirical evaluation of the RSSI from widely used off-the-shelf WiFi cards.

Previous research will be presented in section II. To provide the possibility to repeat, verify and discuss our experiments section III will provide a comprehensive description of our methodology. The RSSI will be evaluated using two different techniques presented in section III-C1 and III-C2. The first technique is based on the libpcap used by previous research in this field. The second one is based on a more recent modification of the Linux driver for Atheros chipsets. It takes advantage of the capability to perform a spectral scan with an increased resolution of the RSSI. We will also provide a comparison to an industrial grade spectrum analyzer using an artificial signal. Section IV provide the reader with results of our experiments in terms of mean variation and distribution of the RSSI. In V we conclude our results and provide future work items.

II. Related Work

In [3] the authors used the RSSI value to provide robotic based location sensing. They measured the distribution of the RSSI in an indoor environment where additional propagation effects like reflection and scattering occur. The authors describe that the distribution were essentially non-Gaussian and non-predictable and worked directly with the measured samples. [4] describes that most of the RSSI value follows Gaussian distribution without providing details on the conducted experiments. [5] identifies the issue that for the

[1]A second application for RSSI interpretation is indoor positioning based on WiFi signal strength.

[2]With "short term environment" we mean that senders and receivers do not move, obstacles (if any) are stable, Fresnel zone is constant (or clear, for the first experiments), and no other senders interfere with our transmission.

simulation of wireless mesh networks a wrong modeling of the distribution of the RSSI can lead to wrong results and questions the commonly used Rayleigh modeling approach.

Robitzsch and Murphy presented in [9] an empirical analysis of 802.11 RSSI values for three Atheros based WiFi cards. They conducted 200 independent experiments per card by transmitting uni-directional data and captured the RSSI using the libpcap. The result show a maximum variation of the measured RSSI mean of $15.5\ dB$ among the independent experiments. In addition to that, the authors describe that "when starting a new run the resulting mean during the first ten of seconds is very often decibels away from the sample mean derived over thousands of packets" [6]. By using a histogram the authors conclude that the RSSI mean does not follow any normal distribution.

In [7] the authors describe that for an indoor environment the mean RSSI is usually modeled as a log-normal distribution when the distribution is symmetric. Their extensive indoor measurement show that most of the distribution ($> 70\%$) are left-skewed[3] and they conclude that signals with stronger power and line-of-sight often have highly left-skewed histograms. The authors calculated the mean variation among different wireless cards and they describe that the mean does not change more than $1.5\ dB$ for most of the cards which stays in contrast to the results obtained in [9]. They also describe that for direct line-of-sight signals the standard deviation of the RSSI increases.

In [10] the authors conducted experiments with four different smartphones obtaining RSSI values from different AP to provide the possibility for an improved indoor WLAN based positioning system. The authors found the RSSI varies greatly (up to $25\ dB$) for different devices. Similar to [7] the authors measured a skewness for the RSSI distribution with a majority to the left ($> 40\%$). Additionally they describe a varying kurtosis[4] for the measured data trending towards a peakedness of the distribution. The authors suggest to change the Gaussian curve fitting by adjusting the standard deviation using the kurtosis values obtained.

III. Methodology

A. Setting up the experiments

Two series of experiments were conducted in two different environments. We started with an indoor laboratory testbed because we intended to replicate the scenario from [9]. We wanted to be able to compare our results with theirs. In this setup, directed antennas were put on 1 m poles and 5 m apart from each other.

Observed results (compare section IV-A) motivated the second setup where we wanted to have a nearly reflection free propagation conditions. For this purpose an outdoor test environment has been set up. Two dipole antenna were placed at a distance of $25\ m$ and at a height of $6\ m$. The tests were conducted on a free field with no reasonable obstacles and rogue WiFi signals nearby. For this placement of the antennas we assume that the effects of ground-reflection can be neglected, which has been theoretically verified by using the concepts of Fresnel zones [15]. The distance between the two dipole antennas was much larger then the Fraunhofer distance [15] which ensured that the receiver operated in the far-field of the antenna.

[3]Skewness is the measure of the asymmetry of a distribution where a value of zero indicates a perfect symmetry. A detailed discussion is available in [8].

[4]Kurtosis measure the peakedness of a distribution while a value of zero indicates no additional peakedness compared to a normal distribution. A detailed can be found in [8].

B. Hardware and Software Configuration

With respect to hardware and software, both series of experiments were identical. Two Alix boards (nodes) were equipped with recent Atheros wireless cards. The nodes were mounted on a pole inside an enclosure and were connected to a dipole using a short pigtail. See table I for a more detailed description.

On both nodes we used Debian with a self-build Linux Kernel based on the revision 3.16. In our tests we strictly configured one node as sender and one node as receiver. Both nodes joined a 802.11a based ad-hoc cell. On the sender we used mgen to generate uni-directional UDP traffic. We set the modulation fixed[5] to the lowest possible value of 6 Mbps. On the receiver we run tshark (a front-end tool for the libpcap) to capture 10.000 packets. In parallel we started the spectrum scanner continuously collecting samples on the same card as long as tshark was running.

TABLE I
Hardware and Software used

System Board	Alix 3D2
WiFi Card	Mikrotik R52HN (AR9220)
Linux Kernel Rev	3.16.7
Libpcap and tshark	1.3.0 and 1.8.2
mgen	v5.02, UDP, 500 PPS, 1450 Byte
802.11	5240 MHz, 6 Mbps

C. RSSI Measuring

We used two different methods to obtain the RSSI values.

1) Libpcap based RSSI: The libpcap has been used in all former publications [6][7][10] in this field of study to obtain the RSSI values. The values are directly reported from the driver. The RSSI is reported on a per packet basis in an integer accuracy. By running a logical monitor interface in parallel to an interface in ad-hoc mode[6] the libpcap[7] reports the RSSI value in the radio tap header. A complete description of the fields defined in this header is available in [11]. In our experiment we concentrated on the evaluation of a single field:

- Antenna signal: "RF signal power at the antenna. This field contains a single signed 8-bit value, which indicates the RF signal power at the antenna, in decibels difference from 1mW." [11]

Additionally we applied a frame type filter for the arriving packets to obtain only the signal values from 802.11 data packets. In particular, this filtered acknowledgements.

[5]This choice will be explained in the results section.

[6]The two logical interfaces are based on the same physical interface.

[7]Which is mostly known for the application wireshark

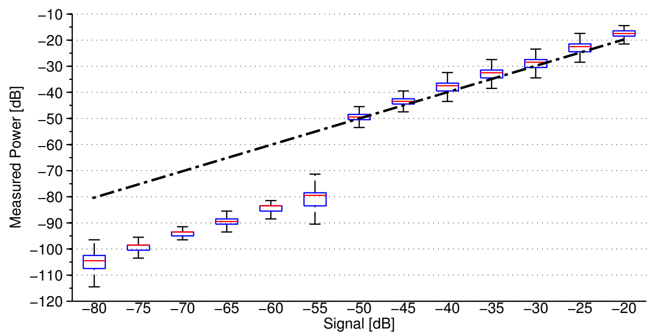


Fig. 1. Spectrum scanner (boxes) vs. Spectrum Analyzer (line).

2) Spectral snapshots FTT based RSSI: The second method to monitor the RSSI of 802.11 data packets is only available for Qualcomm/Atheros AR92xx and AR93xx based chipsets. These NICs have the ability to report FTT data for every OFDM sub-carrier directly from the baseband. This spectral scan feature is implemented in the ath9k and ath10k wireless drivers of recent Linux Kernels. A short description of this feature is available at [12], however, most of the documentation needs be extracted directly from the source of the Linux Kernel.

After triggered from the user space the spectral scan feature reports TLV binary data which includes the absolute magnitude (for the I/Q phase of the wireless signal) for each 56 FTT bins of an 20 MHz 802.11 transmission. The general operation can be summarized as follows: when the spectral scan is triggered through the user space the WiFi NIC enters the spectral scan mode and performs an FFT every 3-4 μs for all sub-carriers independently. This process can be repeated for a specific amount of spectral scans. The computed FFT snapshots are passed to a user space interface where further processing is possible. When a continuous scan is desired the process needs to be retriggered. Additional software is needed to interpret the binary data. A proof-of-concept spectral scan GUI is available at [13] which we used as a basis for our developments. For our experiments we developed a software which processes collected FFT samples and calculates the average power over all OFDM sub-carriers. This calculation is similar to [13] and conducted as follows: the WiFi card reports summarized In-phase and Quadrature data for every sub-carrier.

$$z_i = I_i + Q_i \tag{1}$$

In addition to that the card assumes a fixed noise level N at $-95dBm$ and reports a Signal-to-noise ratio (SNR) for the complete channel in dBm which depends the actual signal and the noise level. The RSSI for each sub carrier can be calculated as follows

$$RSSI_i = N + SNR - 10 * log_{10}(\sum_{i=1}^{56} z_i^2) + 10 * log_{10}(z_i^2) \tag{2}$$

To obtain the overall RSSI we conduct the following operation

$$RSSI = 10 * log_{10}(\sum_{i=1}^{56} 10^{\frac{RSSI_i}{10}}) \tag{3}$$

Before conducting the outdoor test we are interested in the general accuracy of the spectral scan feature. Using an Agilent N5182A signal vector generator and an Agilent CXA n9000a spectrum analyzer[8] we conducted the following experiment in a laboratory environment. We generated an artificial signal at 2.462 GHz which we applied simultaneously[9] to the WiFi card and the spectrum analyzer. We changed the output power level of the signal generator to different values and obtained the channel power from the WiFi card and from the spectrum analyzer. A comparison of the results is shown in figure 1.

We compensate the statical loss of the measurement equipment which leads to the expected line for the Agilent spectrum analyzer in figure 1. Boxplots are used to visualize the results measured with the Atheros WiFi card. For higher Signal levels up to $-50\ dB$ the results for the spectrum scanner and the spectrum analyzer are close. At lower signal levels, the spectrum analyzer and the WiFi card differ by a nearly constant factor of about 25 dB. The box plot reveals that the first measurement after the break implies a larger deviation for the different samples. A clear reason for this break is still unknown. We suspect that at higher signal level the WiFi cards interprets the power as actual signal while for lower level the card monitor the power as an increase in noise.

For our experiments with the WiFi cards the RSSI is saved with a time stamp from the 802.11 Timing Synchronization Function (TSF) which is based on a internal hardware clock on the WiFi NIC. Figure 2(a) illustrates the operation of the spectral scanner and the results from our software.

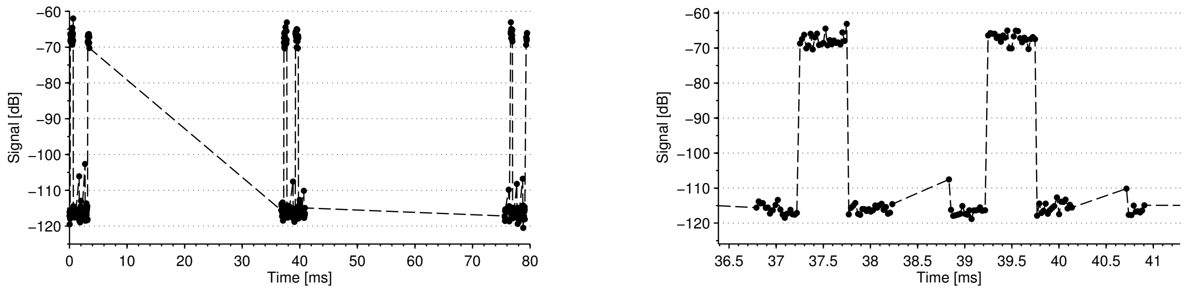
We configured the scanning process to scan 200 samples in parallel with data receive. These samples were processed and saved before the NIC reenters spectral mode. We found that the time between two consecutive scans was approximately 40 ms. In Figure 2(a) the NIC entered the spectral scan mode for three times and collected 200 samples per round. It can be observed that some RSSI values were measured with a signal at approximately $-60\ dB$ and for some samples a noise value of $-110\ dB$ was returned.

A zoom into fig. 2(a) is shown in fig. 2(b). This plot shows the reception of two WiFi packets. Starting at $37.25\ ms$ and ending at $37.75\ ms$ the spectrum scanner captured the reception of a UDP data frame with a payload length of $1450\ Byte$ modulated with a physical datarate of 24 Mbps. The transmission of this type of frame lasted approximately $0.5\ ms$ and we successfully validated this transmission using the equations we presented in [14]. Figure 2(b) reveals an additional finding of the spectrum scanner feature we found during our experiments. The NIC is not capable of operating the spectrum scan in parallel to a data transmission. After the successful reception of the frame (at $37.75\ ms$) the receiver waits a specific Interframe Space (IFS)[10] and sends the acknowledgement. This transmission is not traceable by

[8]Both limited to maximum frequency of 3 GHz

[9]Using a passive high frequency signal splitter and three identical cables.

[10]The IFS after the transmission is to long in this case. Further research is needed.



(a) Spectrum scanner data capturing with 3 scans.

(b) Zoom into a single spectrum scan.

Fig. 2. Spectrum Scanner in operation while receiving 802.11 frames.

the spectrum scanner but leads to a small increase of the noise floor.

IV. Measurements and Results

In the following we will concentrate our evaluation on two main aspects. First we analyzed the mean variation of the RSSI since in [9] a huge variation was reported by the authors. Afterwards we used the spectral scan feature to analyze the probability density function of the RSSI.

A. Indoor

First indoor experiments followed the approach described in [9] as much as possible. Early results were similar to those in [9]. A closer look at the experiment revealed that the WIFI rate adaptation algorithm had a strong influence on the measured RSSI values. So we switched the dynamic rate adaptation off and observed a much more stable and nicely shaped distribution of the RSSI values. However, we still had lots of samples that we could not easily explain. An assumption that reflected signals were disturbing our measurements was verified with the outdoor measurements that followed.

B. Outdoor

Overall 50 independent measurements were conducted at the outdoor environment and between each measurement the WiFi cards were disabled for a short period of time to avoid dependencies between the measurements.

1) Mean variation: The following results are based on the values obtained from libpcap in our experiment. To visualize the results the authors in [9] calculated the sample mean as follows:

$$\hat{x}_{RSSI} = \frac{\sum_{i=1}^{N} x_i}{n+1} \qquad (4)$$

They compared it to the overall experiment mean which is based on all samples obtained $\hat{x}_{\hat{x}_{RSSI}}$. We conducted the same calculations and a comparison between the two results is shown in Figure 3. In these Figures the x-axis represents the measurement time. While [9] uses seconds, we use the unit of received packets which is interchangeable for a constant arrival rate. The y-axis in both plots represents the mean RSSI value after a certain number of packets and is normalized to zero for a better comparability. The 50 conducted independent experiments are plotted in the same figure. Our results indicate a much smaller variation of the mean value of the RSSI among the independent experiments. The maximum variation is about $1\ dB$ in both directions which is close to the value obtained in [7] and significantly less than the $15\ dB$ obtained in [9]. Due to the results of this comparison we believe that the authors in [9] have had a rate adaption algorithm running while conducting the experiment. By dynamically adapting the modulation of the packets the maximum transmission power changes accordingly which can result in the discrete distribution of the average RSSI means shown in Figure 3(b).

The second results we verified using our collected data is the variation of the mean value during the run of a single experiment. As described in [9] there is no common approach to determine the number of packets which need to be captured to derive a representable RSS mean for further processing. Similar to [9] we compare the overall sample mean of a single measurement $\hat{x}_{RSSI}$ to the sample mean after a certain amount of packets have been captured n_p:

$$\hat{x}_p = \hat{x}_{RSSI} - \frac{\sum_{i=1}^{n_p} x_i}{n_p + 1} \qquad (5)$$

where $n_p = \{10, 100, 1000\}$ compared to 10.000 packets for the complete experiment. These values have been calculated for the 50 different measurements and an empirical Cumulative Distribution Function (CDF) is used to visualize the results in Figure 4. This ECDF provides the probability (F(x)) that the mean deviation after a certain amount of captured packets is less then the value shown on the x-axis. For the smallest value of $n_p = 10$ the mean value does not change more than $0.8\ dB$ in both directions compared to sample mean of the complete experiment. After 1000 packets have been captured the mean

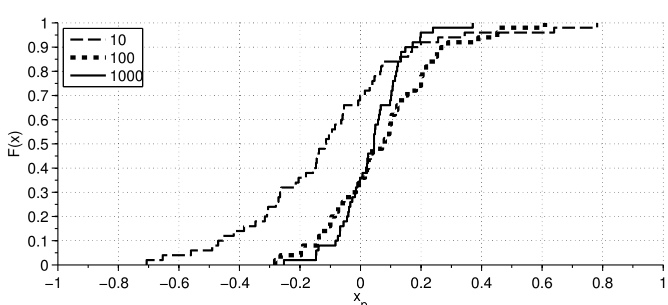
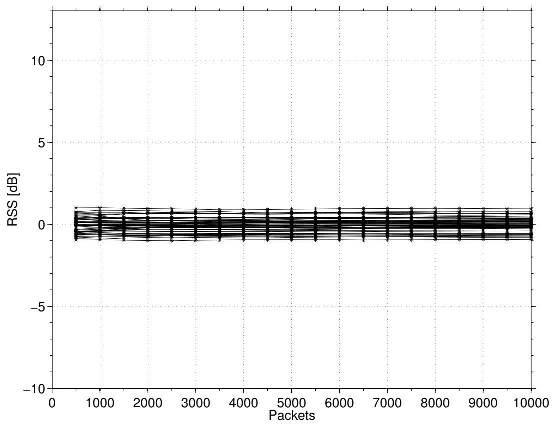
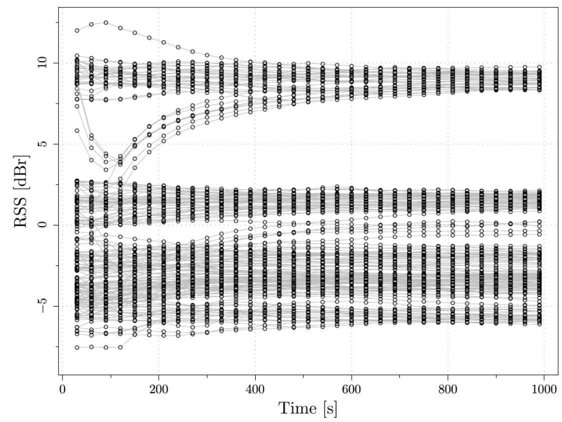


Fig. 4. ECDF for sample mean comparison after a certain amount of packets.



(a) Our Results



(b) Results in [9]

Fig. 3. Sample means ($\hat{x}_{RSSI}$) in reference to the overall mean ($\hat{x}_p$). Comparison between our results and the results obtained in [9].

does not change more than $0.4\ dB$ in 95% of the time. Again, our measured deviation is less then the one described in [6].

2) Receive Signal Strength Distribution: As described in section II different effort has been conducted in the research community to describe the distribution of RSS values of common WiFi transmissions. In this section we present our contribution to this ongoing discussion by exploiting the newly introduced capturing technique based on the spectrum scan as well as additional results from the libcap.

Figure 5 provides two examples for a RSSI histogram based on the same data of one of our 50 conducted experiments. The first Figure 5(a) is based on the RSSI values obtained from the libpcap and the second 5(b) on the evaluated values from the spectral scan feature. Since we are not interested in absolute values we shifted the data by the mean to the origin for better comparison of the two methods. In addition to that we added the normal probability density function based on the mean and the standard deviation of the particular measurement.

As already described in [9] it is a "poor mans choice" to conclude the data distribution from a histogram. Using Figure 5(a) a clear decision can not be drawn because the accuracy of the values is bounded to integer values. Using the spectral scan and evaluating the plot in Figure 5(b) one might conclude that the RSSI can be described to follow a normal distribution. To refine this conclusion we applied three common mathematical distribution tests to determine normality:

- Kolmogorov-Smirnov [16]
- Lilliefors [17]
- Jarque-Bera [18]

At a significance level of 5% all tests reject the null hypothesis that "the data origins from a normal distribution" for all our conducted experiments. When carefully evaluating the data a skewness and kurtosis of the distribution can be obtained as already described in [7].

For the single experiment visualized in Figure 5(b) we calculated a skewness of -0.63 and an excess kurtosis of 3.23. If the samples would follow a perfect normal distribution both values would be equal to 0. In contrasts to previous research we measured a stable left-orientated skewness with a mean of -0.64 and a skewness standard deviation of 0.09. The average kurtosis was measured with 3.42 with a standard deviation of 1.14.

C. Comparison of different cards

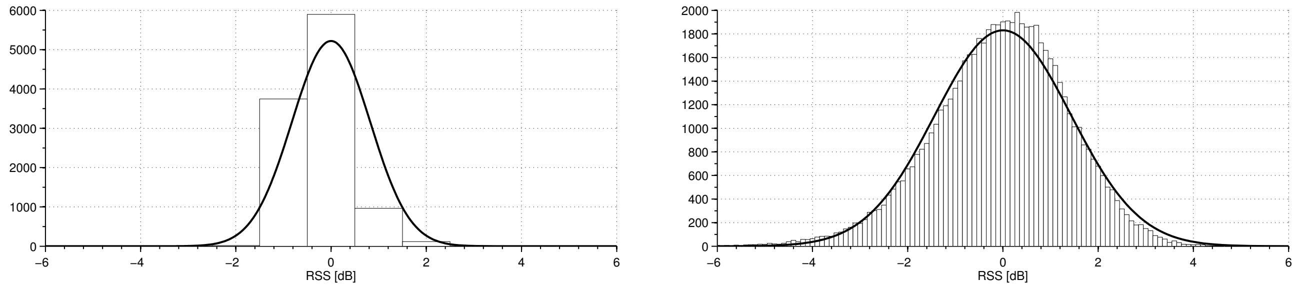
After obtaining the results with two WiFi cards we were interested in the reproducibility of the results with different cards from the same vendor. For this purpose we conducted the same experiment as described in the last section with two additional WiFi cards and we also exchanged the role of transmitter and receiver. The overall results are shown in Table II

TABLE II
SUMMARY OF THE RESULTS FOR DIFFERENT WIFI NICS.

Test	Cards	RSSI Std		Kurtosis	Skewness
		pcap	Sscan	Sscan mean±Std	
1	$1 \mapsto 2$	0.43 dB	0.34 dB	3.42 ± 1.14	-0.64 ± 0.09
2	$2 \mapsto 3$	0.40 dB	0.34 dB	1.84 ± 0.58	-0.45 ± 0.06
3	$3 \mapsto 2$	0.39 dB	0.33 dB	1.68 ± 0.58	-0.43 ± 0.06

The values in table II indicate a small scattering of the results among different WiFi cards while the role of transmitter and receiver has no influence on the results. Further testing is needed to draw a final conclusion about the scattering among different cards since Test 1 was conducted on a different day then Test 2 and 3. The influence of environmental factors (temperature) can therefore not be excluded. However, for all Tests a positive kurtosis and a negative Skewness was obtained in the contemplated outdoor environment.

Due to the measurement environment we used and the greater accuracy of the tools our results indicate that for the scenarios under test, a left-skewness and kurtosis of the RSS occurs in a predictable way. We obtained a steady negative skewness in all our experiments which indicate the trend reported by other researchers [7]. In fact other skewness factors might occur from typical indoor propagation effects or multi-path propagation. For a fixed point-to-point link in a short-term environment the distribution of the RSSI can not be predicted by a normal distribution.



(a) Based on libpcap

(b) Based on spectral scan

Fig. 5. Receive Signal Strength Distribution

V. Conclusion

In this paper we provided an analysis of the RSSI for fixed 802.11 outdoor point-to-point links. We have shown a much smaller variation of the RSSI mean among independent transmissions than reported by other researchers. We have presented a new methodology for obtaining RSSI values based on the spectrum scan feature of recent Atheros/Qualcom WiFi cards. Based on this technique researchers are in the position of providing a much more accurate granularity for RSSI measurements. Our contribution to the state of the art in this field of study includes the first conducted measurement without additional propagation effects like reflections, scattering or interference. This provides the possibility to solely analyze the RSSI for two 802.11 cards transmitting in free space. By applying well-known normality test we have stated out that the RSSI value can not be described by a normal distribution. We measured a constant skewness and kurtosis which may be used to describe the RSSI distribution with other more empirical techniques.

A. Future Work

To obtain more data and to refine our findings we aim at setting up a permanent installation for transmission in free-space. We will study the influence of different parameters on the RSSI distribution. One of these parameters will be the transmission power as reported in [7]. We aim at further investigating the reported difference between the WiFi card and the industrial grade spectrum analyzer.

The quantification of RSS values in combination with the spectrum scanner feature has the ability to monitor the channel and detect interference or propagation issue. Monitoring the transmission at the level of sub-carriers has the advantage that even small interference sources can be identified and a possible switch for the transmission frequency can be conducted. Future work aims at building an interference detector and use it for frequency assignments in long-distance 802.11 networks.

Acknowledgment

The authors would like to thank the participants of the BMBF funded SolarMesh project where part of the needed development took place.

References

[1] T. Zhou, H. Sharif, M. Hempel, P. Mahasukhon, W. Wang, and T. Ma, "A Deterministic Approach to Evaluate Path Loss Exponents in Large-Scale Outdoor 802 . 11 WLANs," *Local Comput. Networks*, no. October, pp. 348–351, 2009.

[2] D. B. Green and M. S. Obaidat, "An Accurate Line of Sight Propagation Performance Model for Ad-Hoc 802 . 11 Wireless LAN (WLAN) Devices," *ICC*, pp. 3424–3428, 2002.

[3] A. M. Ladd, K. E. Bekris, A. Rudys, L. E. Kavraki, and D. S. Wallach, "Robotics-based location sensing using wireless ethernet," *Wirel. Networks*, vol. 11, no. 1-2, pp. 189–204, 2005.

[4] A. Haeberlen, E. Flannery, A. M. Ladd, A. Rudys, D. S. Wallach, and L. E. Kavraki, "Practical robust localization over large-scale 802.11 wireless networks," *Proc. 10th Annu. Int. Conf. Mob. Comput. Netw. - MobiCom '04*, p. 70, 2004. [Online]. Available: http://portal.acm.org/citation.cfm?doid=1023720.1023728

[5] K. Tan, D. Wu, A. Chan, and P. Mohapatra, "Comparing simulation tools and experimental testbeds for wireless mesh networks," *Pervasive Mob. Comput.*, vol. 7, no. 4, pp. 434–448, 2011.

[6] S. Robitzsch and L. Murphy, "Empirical analysis of measured 802.11 receive signal strength values using various Atheros based Mini-PCI cards," *2012 IEEE Int. Symp. a World Wireless, Mob. Multimed. Networks, WoWMoM 2012 - Digit. Proc.*, 2012.

[7] K. Kaemarungsi and P. Krishnamurthy, "Analysis of WLAN's received signal strength indication for indoor location fingerprinting," *Pervasive Mob. Comput.*, vol. 8, no. 2, pp. 292–316, 2012. [Online]. Available: http://dx.doi.org/10.1016/j.pmcj.2011.09.003

[8] K.-H. Hartung, Joachim ; Elpelt, Bärbel ; Klösener, *Statistik : Lehr- und Handbuch der angewandten Statistik*, Oldenburg, 2009.

[9] S. Robitzsch, L. Murphy, and J. Fitzpatrick, "An analysis of the Received Signal Strength accuracy in 802.11a networks using Atheros chipsets: A solution towards self configuration," *2011 IEEE GLOBECOM Work. GC Wkshps 2011*, pp. 1429–1434, 2011.

[10] J. Luo and X. Zhan, "Characterization of Smart Phone Received Signal Strength Indication for WLAN Indoor Positioning Accuracy Improvement," *J. Networks*, vol. 9, no. 3, pp. 739–746, 2014. [Online]. Available: http://ojs.academypublisher.com/index.php/jnw/article/view/12150

[11] J. Berg, "Radiotap.org defined fields," 2011. [Online]. Available: http://www.radiotap.org/Radiotap

[12] A. Chadd, "Spectral Scan Support," 2013. [Online]. Available: https://wiki.freebsd.org/dev/ath_hal(4)/SpectralScan

[13] Simon Wunderlich, "FFT_eval," 2014. [Online]. Available: https://github.com/simonwunderlich/FFT_eval

[14] M. Rademacher, K. Jonas, and M. Kretschmer, "DCF modeling and optimization of long-distance IEEE 802.11n point-to-point links," *VDE ITG-Fachbericht Mobilkommunikation*, vol. 19, 2014.

[15] T. S. Rappaport, "Wireless Communications: Principles and Practice," pp. 1–707, 2002.

[16] F. J. Massey Jr, "The Kolmogorov-Smirnov test for goodness of fit," *J. Am. Stat. Assoc.*, vol. 46, no. 253, pp. 68–78, 1951.

[17] H. W. Lilliefors, "On the Kolmogorov-Smirnov test for normality with mean and variance unknown," *J. Am. Stat. Assoc.*, vol. 62, no. 318, pp. 399–402, 1967.

[18] C. M. Jarque and A. K. Bera, "A test for normality of observations and regression residuals," *Int. Stat. Rev. Int. Stat.*, pp. 163–172, 1987.