Empirical Analysis of Measured 802.11 Receive Signal Strength Values Using Various Atheros Based Mini-PCI Cards

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Abstract—In this paper the accuracy and distribution of measured 802.11 Receive Signal Strength values will be analysed using three different Atheros based cards. The analysis is performed using empirical methods, e.g., sample mean and Empirical Cumulative Distribution Functions, in order to demonstrate the dependency of the accuracy of Receive Signal Strength values on the used chipset and on the number of captured frames to derive the sample mean with a certain probability. A comprehensive section on the experimental environment ensures a possible repeatability of the measurements which underlines the complexity of the performed analysis at the same time.

Keywords—IEEE 802.11 Standards, Statistics, Statistical Distributions, Microwave Measurements, Receive Signal Strength, Atheros, Ubiquity, Wistron

I. INTRODUCTION

Without any doubt WiFi has emerged to a cost-effective last mile access technology for end user devices to provide fast, reliable and low latency wireless connectivity towards the Internet. As the WiFi market penetration has significantly increased over recent years, new solutions and algorithms taking advantage of this technology are usually just a matter of time until they appear. With the increase of WiFi enabled devices, the number of deployed Access Points (APs) also steadily increased which is ideal for automated localisation position determination algorithms. These solutions are based on the Receive Signal Strength (RSS) of received packages from various APs to determine the device’s location. As it will be described in detail later on, there is a vast literature on the accuracy of 802.11 RSS values reported by a WiFi card in relation to indoor positioning determination. However, to the best of the author’s knowledge none of the previous works focused on fundamentals such as:

- Is there a significant difference in the RSS accuracy provided by different WiFi cards
- What RSS accuracy can be expected based on the number of captured IEEE 802.11 frames
- Is there a significant difference between radios operating in the 2.4 and 5 GHz frequency band

As there is no consistency throughout the research community on how many RSS samples are required to reach a certain accuracy, the presented work is going to investigate this gap using various 802.11a/b/g cards from multiple vendors. For completing the motivation of the presented research, WiFi can also be used to span a Wireless Mesh Network (WMN) in order to provide a cost-effective and easy to deploy solution for a last mile back-bone network. As capacity and latency constraints of single-radio Mesh Nodes (MNs) requires an increase of the overall MN’s network performance, the solution of equipping each MN with multiple back-bone radios becomes highly interested. This solution could lead to strong interferences among the radios of an MN, namely Adjacent Channel Interference (ACI) and Inter Channel Interference (ICI), which require algorithms to determine the level of interference in order to apply frequency multiplexing techniques to cope with these physical effects. Such an algorithm will derive the level of ACI and ICI between two radios from a measured RSS which requires to be very accurate (granularity $\leq 1$ dB). A significant step towards such a solution has been published in [1], which proposes a Slope-Intercept approach to decide on an accurate RSS value. However, as it will be observed in this paper, the accuracy in terms of the probability that a calculated RSS value will fall into a given range varies significantly for various reasons. Thus, the developed Slope-Intercept algorithm published in [1] cannot be applied to random 802.11 cards and actually works as the main motivator for the presented work.

The remainder of the paper is structured as follows. Section II will give an overview of the related work which is associated with location determination approaches. Section III will introduce the hardware used for this analysis as well as further preliminary considerations in order to back up the results presented in Section IV. The paper is then concluded in Section V.

II. RELATED WORK

As previously mentioned, obtaining accurate RSS values from 802.11 interfaces has been rather of interest to researchers within the localisation determination domain than to researchers within the WMN domain. This is why the
related work is only pointing to published research from this area. In order to structure this section and to present the vast literature on this topic in a logical way all related work will be presented chronologically.

One of the most cited work in this area is a Radio Frequency (RF) based system, namely RADAR, that determines a user’s location by evaluating measured RSS values captured from its surrounded 802.11 APs, [2]. The approach chosen by Bahl et al. is straight forward. Firstly they collect 20 RSS samples per detected AP, secondly they calculate a mean over the 20 captured samples and thirdly they derive the location based on the means from all APs in physical range.

Following the same approach, Roos et al. were also using 20 RSS samples (called observations by Ross et al.) to compare the accuracy of various localisation methods. However, as for [2], [3] also never states on which frequency band they were operating while running the experiments and not to mention the experimental setup which makes it hard to further develop the observations.

To the best of the author’s knowledge, the first work that has studied the distribution of measured RSS values in more detail was published in 2002 by Ladd et al., [4]. In order to carry out the experiments the authors were using an 802.11b LinkSys PCMCIA radio with an Intersil chipset plugged into a laptop that run a Linux operating system. They also state that the collection of RSS values was based on the probe request/response facility provided by 802.11 for actively scanning for APs. The presented histograms in [4, Figure 3] indicate that the authors were extracting the Receive Signal Strength Indicator (RSSI) value from the Prism header which is however only a unit-less value and has to be converted back to decibels relative to 1 milliwatt (mW) (dBm) using a vendor specific converting table which has not been provided. When trying to compare the histograms published in [4] with results from other researchers, this could lead to wrong conclusions since RSS values in dBm have been used across all other papers. Additionally, Ladd et al. have observed that the orientation of the client towards the AP matters when measuring the RSSI, as also stated in [2]. This observation should be carefully scrutinised due to the usage of a laptop which has its WiFi antenna(s) usually placed around the screen and does not represent an ideal dipole antenna (omni-directional antenna) in order to be independent from the orientation towards the AP. This would explain the diverse RSSI histograms obtained in [4, Figure 3] and leaves the floor open for interpretation how the authors derived a general cumulative error distribution for measured RSSI values.

Moving forward in time, Xiang et al. investigated further the determination of a user’s location by realising the irregular pattern of RSS histograms when repeating measurements which is due to “multipath effects, dead spots, noise, and interference in an indoor environment”, [5]. More importantly, the authors increased the number of collected RSS values for deriving a distribution histogram to 300 samples per run. As in [4], also Xiang et al. used a laptop with an integrated 802.11 adaptor and discovered different RSS histograms for different orientations towards the AP, [5, Figure 3]. Thus, the observed histograms and their derived probabilities should be carefully referenced when analysing the reported RSS values from 802.11 cards. Additionally, Xiang et al. state that they had measured the RSSI (which is unit-less) but all figures are clearly depicting RSS values.

The first publication that rather focuses on the distribution of measured RSS values has been conducted by Kaemarungsi et al., [6]. Besides considering various WiFi cards from different vendors, the authors captured always 1800 beacons within the 2.4 GHz frequency band in order to calculate an RSS mean value. More interestingly, they have discovered that the RSS distribution is significantly skewed but not always left- or always right-skewed. As proven by Sheng et al., [7, Figure 5], in case an RSS histogram of a single run has two main peaks, as depicted in [6, Figure 7] without any explanation, this is likely to be the effect of antenna diversity. Sheng et al. even increased the number of injected frames to 3,000 in order to derive the RSS sample mean and to prove the antenna diversity phenomenon. The authors in [7] are also stating that the resulting distribution of measured RSS values follows a Gaussian Distribution; in case of antenna diversity enabled the distribution can be represented with a Gaussian Mixture Model (GMM). As it can be seen later in this presented work, the distribution of measured RSS values is far away from normal distributed for the individual cards used to perform this work.

III. PRELIMINARY CONCERNS

In order to provide a comprehensive and sophisticated analysis of measured RSS values this section will describe the used hard- and software for conducting the experiments. Additionally, some important aspects regarding antenna diversity will be discussed in detail.

The title of this paper has already indicated the focus on Atheros based 802.11 cards, mainly because of the following reason. The presented work is a small piece towards a Linux-based Self-Configuration Framework (SCF) for WMNs which requires full control over the WiFi card in terms of changing the mode (client, ad-hoc, access point or monitor mode), setting the transmission power and other important settings. To date, the Linux kernel only provides this comprehensive amount of settings for Atheros based chipsets. Other chipsets from Intel or Broadcom get recognised by the kernel due to proprietary modules by the individual vendors, however, these drivers do not allow the same level of configuration as the Atheros Linux driver does. Table I depicts the chosen Atheros cards which will be analysed regarding their reported RSS accuracy. Besides the card’s exact name, the used frequency band and whether
Table I

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Ubiquity XR2</th>
<th>Ubiquity XR5</th>
<th>Wistron CM9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chipset (lspci)</td>
<td>AR5213</td>
<td>AR5413</td>
<td>AR5212/5213</td>
</tr>
<tr>
<td>Chipset (label)</td>
<td>AR5414</td>
<td>AR5414</td>
<td>AR5213A</td>
</tr>
<tr>
<td>MAC</td>
<td>802.11b/g</td>
<td>802.11a</td>
<td>802.11a/b/g</td>
</tr>
<tr>
<td>Diversity</td>
<td>✓</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

the card supports antenna diversity or not. Table I comprises the exact chipset number, both what the Linux kernel reports and what the card’s cover label states.

All measurements have been conducted indoors and during non-office hours. Initial experiments during office hours had shown a random behaviour of the reported RSS due to moving people which made it impossible to derive sophisticated results form these measurements. The distance between the sender and receiver was set to 5m and it had been ensured that the first and second Fresnel zone was completely free from any obstacles. In order to cope with the RSS effect of antenna diversity, as investigated in [7] and [8], the diversity for the Ubiquity XR2 card had been switched off. This also ensures a fair comparison among all analysed cards. All senders were alix1d embedded boards with Voyage Linux version 0.7.5 and Multiband Atheros Driver for Wireless Fidelity (MadWiFi) version 0.9.4 Subversion (SVN) revision 4178 installed. All receivers were proper desktop machines with a dedicated mini-PCI to PCI converter and Debian Edge as the operating system. Both sender and receiver have been using omni-directional antennas for eliminating any orientation effect, as reported in [2], [4], [5] and [9]. During all measurements the 802.11 links have been saturated with injected User Datagram Protocol (UDP) traffic. The separation from data and management frames as well as the RSS and Noise Floor (NF) extraction from the Radiotap header had been realised using Tshark.

As it has been observed in [1], not only does the proprietary Atheros feature Ambient Noise Immunity (ANI) affect the reported NF negatively, it also affects the reported RSS and leads to wrong values. This faulty behaviour of the card has been also taken into account when evaluating the results in this work.

IV. RESULTS

This section will eventually present the results of the empirical RSS analysis. While Sub-Section IV-A solely focuses on the presentation of RSS sample means for the three investigated 802.11 cards, Sub-Section IV-B will evaluate the results by deriving mean probabilities from Empirical Cumulative Distribution Functions (ECDFs). Finally, Sub-Section IV-C will show whether a set of RSS values is following a Gaussian distribution or not.

Before presenting the first results some preliminary explanations will be given regarding the statistical analysis. As the mean \( \mu \) of a set of RSS samples \( x \) does not necessarily represent the real RSS mean of the electromagnetic wave reported by the card, the mean that has been calculated this publication is the sample mean \( \bar{x} \) - or also called population mean. This can be explained by the fact that with every new gathered RSS sample the chance that the sample mean changes again is always given. A widely used example of this hypothesis is the task of obtaining the opinion of a population in a country represented by a mean value. For this task a set of individuals \( n \) will be questioned and upon their answers a population mean can be derived. However, with only one further opinion (set of individuals is now \( n+1 \)), the mean could change and the previously calculated population mean does not represent the actual mean. Hence, the population mean is calculated with:

\[
\bar{x}_{RSS} = \frac{\sum_{i=1}^{n} x_i}{n+1} \tag{1}
\]

For completeness of this publication and in honour of the effort in creating this open-source solution it is worth mentioning that all results and figures have been obtained using the statistical computing software R [10].

A. Receive Signal Strength Sample Mean Values

This section will now present calculated continuous sample means of all three cards. In all depicted results in this sub-section the x-axis depicts the experimental run-time \( t \) and the y-axis the calculated continuous RSS sample mean \( \bar{x}_{RSS} \) at time \( t \). For increasing the comparability among all plots, an overall sample mean \( \bar{x}_{RSS} \) was derived from all sample means \( \bar{x}_{RSS} \) in order to only plot them in relation to each other. Hence, the y-axis depicts sample mean decibel values in reference to \( \bar{x}_{RSS} \) (0 dBr) obtained at time \( t = 960 \) s.

As can be observed from Figure 1, 2 and 3, the individual sample means \( \bar{x}_{RSS} \) are anything but always close to the reference sample mean. When comparing the range in which the RSS sample means are located the XR2 sample means are within \(-4 \) dBr < \( \bar{x}_{RSS} < 4 \) dBr, the XR5 sample means within \(-5.5 \) dBr < \( \bar{x}_{RSS} < 10 \) dBr and the CM9 sample means within \(-7 \) dBr < \( \bar{x}_{RSS} < 6 \) dBr. This clearly indicates that when obtaining an RSS sample mean, even when conducting a long-term run, the resulting value is anything but accurate and reliable especially when repeating the trial. However, to date it can be only assumed that the reason for this phenomenon is probably due to the card’s amplifiers which do not work that accurate. What is also notable are the resulting blocks in which several sample means are somehow bundled, especially observable for the XR2 and XR5 card.

As already investigated in [1], when starting a new run the resulting sample mean during the first tens of seconds
is very often decibels away from the sample mean derived over thousands of packets. This can be observed from Figure 2 in which especially the sample means between 7 dBr and 10 dBr only becomes flat after 400 s.

**B. Sample Mean Accuracy After Certain Times**

As described in Section II, there is no common approach within the research community on how many 802.11 frames should be captured in order to derive a sophisticated and representable RSS mean. Moreover, as observed in the previous section, even the resulted RSS sample mean after a long-term run does not necessarily provide a fine granularity. Thus, in this sub-section the sample mean $\bar{x}_{RSS}$ of an individual run at time $t = 960$ s will be compared with the sample mean of the first $n_f$ RSS values:

$$\bar{x}_{t,f} = \frac{\sum_{i=1}^{n_t} x_i}{n_t + 1} - \frac{\sum_{i=1}^{n_f} x_i}{n_f + 1}$$

(2)

where $n_f = \{10, 100, 1000, 10000, 100000\}$ and $n_t = 960$ s. The resulted 200 sample means $\bar{x}_{t,f}$ are then evaluated using an ECDF in order to give the probability that $\bar{x}_{t,f}$ would fall into range $x_1 \leq \bar{x}_{t,f} \leq x_2$ when repeating this experiment. All figures also comprise horizontal lines for $P = \{50, 95\}$ %.

When interpreting Figure 4 for the XR2 card, it can be observed that for a probability $P = 95\%$ $\bar{x}_{t,f}$ with $n_f = 10$ would fall in range \(-0.8 \text{dB} \leq \bar{x}_{t,f} \leq 0.8 \text{dB}\) which is already very accurate and indicates very little deviation of $\bar{x}_{RSS}$ over time. When increasing the number of frames...
$n_f$ used to derive $\bar{x}_{t,f}$, the resulting sample mean becomes extremely close to $\bar{x}_{RSS}$ after 960 s. For the XR2 card can be concluded that with 100 000 frames the probability that sample mean will not change anymore by more than 0.1 dB is 95 %. Moving to the XR5 card, Figure 5 depicts a much different behaviour compared to Figure 4. First, the symmetry of the cumulative function, as for the XR2 card, is not given anymore for $n_f = \{10, 100\}$. As observed in [1], in most cases the sample mean $\bar{x}_{RSS}$ will change to higher power values over time. For $\bar{x}_{t,f}$ with $n_f = 10$ the ECDF is extremely right-skewed which proves the claim in [1]. Also, the XR5 card does not provide the same accuracy as the XR2 card, as can be observed for $n_f = 100$ 000.

As for the XR5 card, also the achieved sample mean $\bar{x}_{t,f}$ for the CM9 one, depicted in Figure 6, does not provide the same accuracy as the XR2 card. It is strongly believed that this is related to the lower frequency band in which the XR2 card was operating, i.e., 2.4 GHz instead of the 5 GHz band. But the extreme right-skewed observation for the XR5 card cannot be confirmed for the CM9. Furthermore, for all $n_f$ expect $n_f = 10$ the ECDFs are almost identical which leads to the conclusion that capturing more than 100 frames does not significantly improve the accuracy of $\bar{x}_{RSS}$.

C. Analysis of Receive Signal Strength Distribution

The null hypothesis that a set of RSS values does follow a Gaussian distribution or can be represented with a GMM, as claimed in [6] and [7], respectively, will be now analysed. In order to increase the comparability among Figure 7, 8 and 9, the RSS values have been again normalised in reference to their overall sample means. Moreover, as a histogram is known as a "poor-man’s-choice" to derive the distribution of the gathered values, two Gaussian distributions $N_{\bar{x}}(\bar{x}, \sigma_{\bar{x}})$ and $N_{\tilde{x}}(\tilde{x}, \sigma_{\tilde{x}})$ have been plotted additionally into the figures in order to compare the obtained histogram directly with the corresponding Gaussian distribution. Note, the range of each the x-axis represents the range of captured RSS values.

Starting again with the XR2 card, Figure 7 depicts a quite narrow and slim histogram which supports the corresponding ECDF from Figure 4. But more interestingly, $N_{\bar{x}}$ and $N_{\tilde{x}}$ do not fit at all to the histogram which clearly rejects the null hypothesis by [6] and [7] for the XR2 card. Figure 8 depicts the histogram for the Ubiquity XR5 card and as for the XR2 one the applied Gaussian distributions $N_{\bar{x}}(\bar{x}, \sigma_{\bar{x}})$ and $N_{\tilde{x}}(\tilde{x}, \sigma_{\tilde{x}})$ are far away from being an accurate representation of reported RSS values. Finally, Figure 9 depicts the histogram for the Wistron CM9 card and without any doubt the null hypothesis that the RSS follows a Gaussian distribution has been clearly rejected for all tested cards.
RSS [dBr]
−50 −40 −30 −20 −10 0 10
0e+00 1e+07 2e+07 3e+07 4e+07

Figure 8. Empirical Cumulative Distribution Function of individual, normalised Receive Signal Strength values for the Ubiquity XR5

RSS [dBr]
−15 −10 −5 0 5 10 15
0.0e+00 5.0e+06 1.0e+07 1.5e+07 2.0e+07 2.5e+07 3.0e+07

Figure 9. Empirical Cumulative Distribution Function of individual, normalised Receive Signal Strength values for the CM9

V. CONCLUSION

The presented work has been analysed the accuracy and distribution of measured RSS values for the selected Atheros based 802.11 cards using empirical methods. It has been shown that when repeating an RSS measurement the resulting RSS sample mean is likely to vary significantly from the previous one with different levels of probabilities for each card. ECDFs have been used to derive probabilities that the sample mean will fall within a defined range. It has been also shown that a set of RSS values does not follow a Gaussian distribution, as stated in some literature. It is considered to perform further experiments in order to clarify claims in [6] that an RSS distribution changes when increasing the distance between sender and receiver. Furthermore, it will be investigated if the distribution changes when RSS values are solely taken from management frames instead of data frames.

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