On the relationship between received signal strength and received signal strength index of IEEE 802.11 compatible radio trannsceivers

Attila Buchman
Faculty of Informatics
University of Debrecen
Debrecen, Hungary
buchman.attila@inf.unideb.hu

Claudiu Lung
Faculty of Engineering
Technical University of Cluj-Napoca
Cluj-Napoca, Romania

***Abstract*—Every WiFi, ZigBee or Bluetooth compatible radio chip provides a byte of information related to the received signal strength (RSS), the so called received signal strength index (RSSI). In a given point in space, on a specific radio channel, the RSS has a unique value at a given moment in time. Still, radio chips produced by different manufacturers will report different RSSI numbers. So RSSI is only related to, but not identical to RSS. In this paper, a formula that relates RSS and RSSI is derived. The validity of this theoretical assumption is tested on various vendors' data. For Microchip's MRF24WB radio chip the testing is done experimentally.**

***Keywords*—received signal strength; received signal strength index; dBm; netvork interface card; WiFi; RF;**

I. MOTIVATION

The subject of this paper is related to RF map based indoor localization [1-8]. Several versions of this method were implemented [12, 13]. Some of them make use of the existing WiFi LAN infrastructure. In this case a so called RSS map of the building is first recorded. This is a simple data base containing records like (1).

$$R_k=\{(AP_{k1},RSS_{k1}), (AP_{k2},RSS_2), \ldots, (AP_{kN},RSS_{kN})\} \quad (1)$$

In (1) $k \in (1, M)$ is an integer that stands for the location identifier, M is the total number of points on the map and N is the number of access points considered for localization.

In order to locate a mobile device in the mapped environment one needs the "fingerprint" of the actual location of the device i.e. a record like in (2).

$$R_x=\{(AP_{x1},RSS_{x1}), (AP_{x2},RSS_2), \ldots, (AP_{xN},RSS_{xN})\} \quad (2)$$

R_x wil be compared to all R_k and if the best fit is for $k=i$ than $x=i$, that is the device is in location i.

If the mobile device is a laptop, tablet or smartphone, then things go well because they all can report actual RSS readings in *dBm* (dB related to 1mW), so one RSS map can be used with several devices. But when simple embedded system are used, one must take into account that IEEE 802.11 compatible radios report a RSS index (RSSI) which is usually not equal to RSS and is also different from one manufacturer to another. So their reports must be translated in standard RSS units in order to locate them using the same map.

Each vendor may or may not offer means (formula, lookup table) to derive RSS from his specific RSSI but in this paper we propose a general relationship between these values. The experimental proof of our theoretical assumptions is also presented in the particular case of MRF 24WB radio transceiver.

The rest of this paper is organized as follows: based on some practical assumption related to the way that a generic radio receiver is built, section II gives a theoretical derivation of the relationship between RSS and RSSI. Section III presents IEEE 802.11 specifications referring to RSSI and how this byte of information is used inside and outside of WLANs. Section IV presents formulae and lookup tables given by vendors to relate RSS to RSSI. As one shall see they are compatible with our assumptions. Section V is about experimentally establishing a *RSS=f(RSSI)* relationship and section VI presents the experimental results. Section VII concludes this paper.

II. THEORETICAL CONSIDERATION

Every radio receiver has a mean to detect, at the output of analog frontend stages, the average signal (specifically voltage) level. This voltage is used to control the gain of the RF and IF amplifiers. The process is called automatic gain control (AGC) and goes like this (refer to fig. 1):

(i) If V_L is beyond V_{REF} (so the input signal is weak) the AGC will exert no influence on the RF or FI amplifiers enabling them to work at full gain.

(ii) If V_L exceeds V_{REF} the AGC will act to reduce the gain of FI amplifier stages.

(iii) If that is not enough (for $V_L \approx V_{REF}$) than the gain of RF stages will also be reduced.

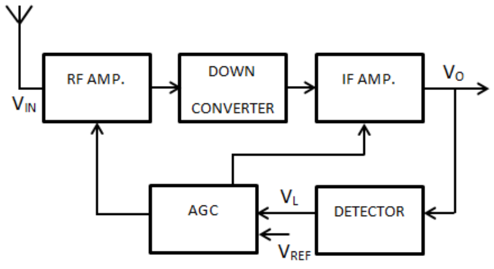


Fig. 1. Analog frontend of a generic radioreceiver.

As a consequence the overall gain is a function of the input signal level: the weak signals are fully amplified while stronger signals are less amplified. This resembles to a logarithmic amplifier and one may approximate V_L as being:

$$V_L \approx A \cdot \log(V_{IN}) + B \tag{3}$$

In (3) A and B are just some constants for a specific radio receiver, but still can have different values from one manufacturer to another.

Instead of voltage levels in telecommunication one deals with power levels. Taking into account that:

$$P_{IN} \propto V_{IN}^2 \tag{4}$$

equation (3) can be re-written as:

$$V_L \approx A \cdot \log\left[k \cdot (P_{IN})^{1/2}\right] + B \tag{5}$$

In (5) k is again some constant standing for the effect of the input impedance on the input power. Taken into account the proprieties of logarithms (5) still can be written in a format that is similar to (3), but relates V_L to the input power:

$$V_L \approx C \cdot \log(P_{IN}) + D \tag{6}$$

Of course, now we have new constants (denoted C and D) but a linear relationship between V_L and the logarithm of the input power.

Even if mathematically may not be the most rigorous, the above demonstration shows that the voltage controlling the AGC loop (V_L) can be used as a measure of the received signal power.

In fact we assume that this is what radio chip manufacturers do: V_L, after analog to digital conversion is presented as *RSSI*, by consequence (7) stands.

$$RSSI \propto V_L \tag{7}$$

On the other hand, $log(P_{IN})$ is related to *RSS* as in (8):

$$RSS \equiv 10 \cdot \log\left(\frac{P_{IN}}{P_0}\right) \tag{8}$$

where P_0 is a reference power level.

Usually (for WiFi, Bluethoot and 802.15.4 compatible radios at least) $P_0=1mW$. That is why one can say that *RSS* is expressed in *dBm*, (*m* standing for *mW*).

Taking into account (6), (7) and (8) one can conclude that *RSS* must be related to *RSSI* as in (9).

$$RSS \approx \alpha \cdot RSSI + \beta \tag{9}$$

In (9) α and β are just dimensionless constants, parameters specific to each radio manufacturer. So a linear relationship seems to exist between *RSS* and *RSSI* values. We will test this relationship, with manufacturer data and experimental measurements to.

III. IEEE 802.11 AND RSSI

The IEEE 802.11 standard recommends (but IEEE 802.15.4 specifically asks) for the physical layer (PHY) to supply one byte of information called RSSI relative to the received signal strength (RSS). The signal strength is supposed to be observed between the beginning of the start frame delimiter and the end of the PLCP header error check [8, 10]. The standard does not specify how this RSSI should relate to RSS. That is why it’s hard to compare RSSI readings from different vendors.

A. *Making use of RSSI internally*

With or without any recommendation coming from IEEE standard committees, radio chip manufacturers still have to provide means to detect radio energy in a specific channel, prior to start any data transmission or reception. Moreover, even the decision to connect to a specific access point (AP) relays on signal strength information. In the specific case of IEEE 802.11 compatible radio communication:

(i) Prior to any data transmission a so called clear channel assessment (CCA) routine is performed in order to avoid collisions with already transmitting stations. CCA can only be done if one has means to detect and quantify radio energy in a specific channel. *RSSI* is very well suited, in fact is generated for this purpose.

(ii) In order for the receiver to capture incoming messages a so called carrier sense (CS) routine must be performed. In fact CS is performed permanently, by every radio chip, if not in sleeping or transmitting mode. Carrier sensing is nothing more than radio signal strength evaluation on a specific channel. For this purpose to, *RSSI* comes in handy.

(iii) While roaming or before any connection attempt, stations performs scans of the radio channel, observing *RSSI* values from different AP (if any) in range. Decision to disconnect from or to connect to one specific AP or another is taken considering their respective *RSSI* levels.

B. *Making use of RSSI externally*

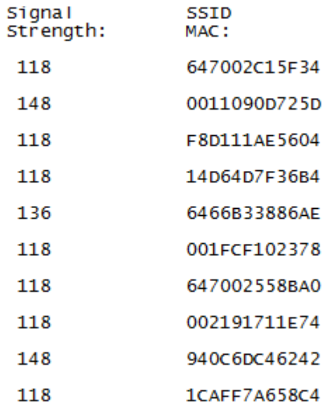
If *RSSI* would be used only in-chip for communication related tasks (CS/CCA/roaming) there would be of no interest to us what the actual relationship between *RSS* and *RSSI* is. But *RSSI* has shown to be useful in at least another application area: indoor localization and positioning.

While outdoor localization, due to GPS technology is a closed issue, indoor localization is far from being so. The reason is simple, GPS signals cannot be detected indoors. As an alternative, a handful of technique where proposed, tested and used:

- ultrasonic echo location,
- infrared localization,
- computer vision and image recognition,
- *RFID* based technologies,
- *RF* based methods:
    - time-of-arrival (*TOA*)
    - *RSSI*

All these technologies except for the last (*RSSI* based RF) have a major drawback: the need for an application specific hardware infrastructure to be deployed. This makes them costly and not user friendly at all.

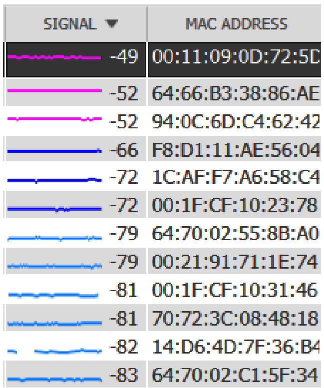
RSSI based RF technology also needs a specific infrastructure but (at least in urban areas) that is already present: the ubiquitous WiFi LAN infrastructure. Performing a passive scan any WiFi enabled device would get a so called *RSS* fingerprint of the specific spot in which it is momentarily located. Several techniques exist to locate the device based on this *RSS* fingerprint. Figure 2 shows an example of what such a passive scan report would look like for a MRF24WBOMA radio chip (other information that comes as passive scan results but are irrelevant for localization purposes where discarded).



```
Signal           SSID
Strength:        MAC:

 118             647002C15F34

 148             0011090D725D

 118             F8D111AE5604

 118             14D64D7F36B4

 136             6466B33886AE

 118             001FCF102378

 118             647002558BA0

 118             002191711E74

 148             940C6DC46242

 118             1CAFF7A658C4
```

Fig. 2. Results of a passive scan performed with a MRF24WBOMA radio.

The same scan was performed, in the same spot, shortly after the first, but using a laptop with an Intel(R) WiFi Link 1000 BGN network interface card (NIC). The results are shown in figure 3.



SIGNAL ▼	MAC ADDRESS
-49	00:11:09:0D:72:5D
-52	64:66:B3:38:86:AE
-52	94:0C:6D:C4:62:42
-66	F8:D1:11:AE:56:04
-72	1C:AF:F7:A6:58:C4
-72	00:1F:CF:10:23:78
-79	64:70:02:55:8B:A0
-79	00:21:91:71:1E:74
-81	00:1F:CF:10:31:46
-81	70:72:3C:08:48:18
-82	14:D6:4D:7F:36:B4
-83	64:70:02:C1:5F:34

Fig. 3. Results of a passive scan performed with a Intel(R) WiFi Link 1000 BGN NIC.

One can observe that the signal strength values are not the same. Taking for example the AP with MAC address …5D (first row in fig. 3, second row in fig. 2) the values are not only of opposite polarity but the absolute value is also different: 49 vs. 148. And that goes for every AP in the previous examples.

An important observation must be derived here: while observing the same reality (*RSS*), different radios report different results (*RSSI*). While *RSSI* is used internally this fact is irrelevant. But when it comes to use *RSSI* readings externally this inconsistency became cumbersome. What would be the result of a localization attempt if the *RSS* map was recorded with the Intel NIC from the previous example and the fingerprint is taken with a MRF24W radio device?

It is therefore of utmost importance to have means to translate various type of *RSSI* readings into some standard *RSS* metric.

IV. RELATIONSHIP BETWEEN RSSI AND RSS

As we previously stated several IEEE standards (802.11, 802.15.4 to name just two of them) ask for *RSSI* to be accessible. But there are no requirements in those standards that the relationship between *RSSI* and *RSS* should be revealed. This mater is of no importance for the scope of those standards. Therefore, different WiFi radio vendors may have different policies regarding this issue.

(i) There are some vendors (like Intel) which provide *RSS* directly, in dBm. For their radios *RSS* = *RSSI*. That’s one of the reasons why, there is some degree of confusion regarding the proper usage of these terms.

(ii) Other vendors (like Atheros) provide formulae to compute *RSS* based on *RSSI* readings. These formulae are usually very simple, something like $RSS=RSSI-k$, with k being a constant.

(iii) There are vendors (Symbol, Cisco) who give more or less fine grained lookup tables which relate every possible *RSSI* reading to the corresponding *RSS* value.

(iv) Finally there are vendors (Microchip) who, after our best knowledge haven’t published yet information to relate *RSSI* to *RSS* for some of their newest radio chips. In this case the relationship between *RSS* and *RSSI* should be derived empirically.

In our opinion, eq. (9) can always be used to express the relationship between *RSSI* and *RSS*. In order to prove that, let's apply (9) using some actual vendor data taken from [9].

A. The case of Intel transceivers

Intel makes the life easy in this field: theirs NICs, as previously stated, provide *RSS* in dBm directly. This is a particular case of eq. (9), for $\alpha=1$ and $\beta=0$.

B. The case of Atheros transceivers

Atheros is one of those vendors that offer a formula to compute *RSS* based on *RSSI* readings:

$$RSS = RSSI - 95 \tag{10}$$

Comparing (10) and (9) one can see that (10) is a particular case of (9), for $\alpha=1$ and $\beta=-95$.

C. The case of Symbol transceivers

Symbol gives a very coarse grained lookup table to convert *RSSI* to *RSS*. There are only six entries in this table:

```
RSSI ≤  4 is considered to be -100dBm
RSSI ≤  8 is considered to be -90 dBm
RSSI ≤ 14 is considered to be -80 dBm
RSSI ≤ 20 is considered to be -70 dBm
RSSI ≤ 26 is considered to be -60 dBm
RSSI ≥ 32 is considered to be -50 dBm
```

Except for the first row, any other two rows in this table allows us to fit this data to eq. (9). In a straightforward manner one can show that this table is generated by (9) for $\alpha=1.666$ and $\beta=-103.333$.

D. The case of Cisco transceivers

Unlike Symbol, Cisco gives a very fine grained lookup table to convert *RSSI* to *RSS*. There are no less than 100 entries in this table so we will present it in a graphical manner (see figure 4.).

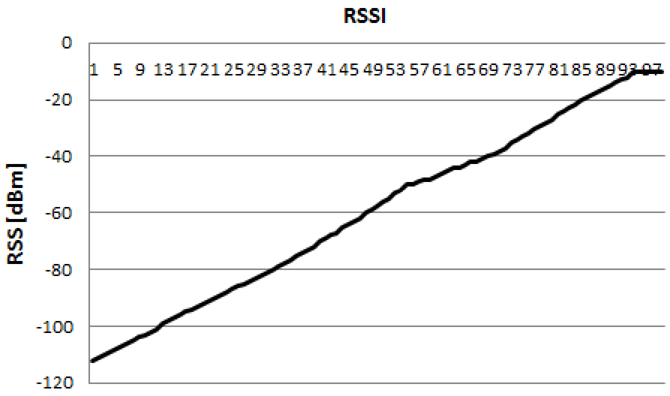


Fig. 4. RSS as a function of RSSI for Cisco routers

As one can see in fig.4, the relationship is very close to linear so eq. (9) would represent a very good approximation. It is given in the table (it may not be so obvious in the graph) that for *RSSI=0* the *RSS* value is *-113*. By consequence (see eq. 9) $\beta=-113$. The slope (α) can be approximated with:

$$\alpha \approx \frac{\Delta RSS}{\Delta RSSI} = \frac{-12-(-113)}{93-0} = 1.086 \tag{11}$$

E. The case of MRF24W transceivers

Since after our best knowledge, the manufacturer did not provided yet any means to relate *RSS* and *RSSI*, this task should be done experimentally. Our approach was to compare *RSSI* readings gained from a MRF24WBOMA radio chip with *RSS* levels reported by an Intel WiFi Link 1000 NIC and then to find the values of α and β that would give the best fit with respect to (9).

V. EXPERIMENTAL WORK

In order for us to find α and β values that gives the best *RSS* estimate for MRF24WB radios several measurements where performed. The experimental setup is presented in fig. 5.

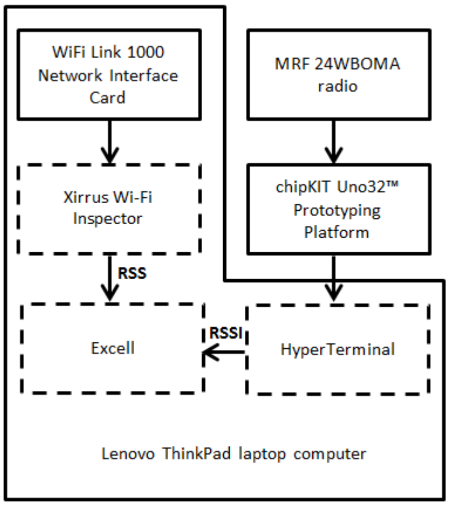


Fig. 5. Experimental setup

The main components and their role in this setup are as follows:

(i) The device under test is MRF24WBOMA, an 802.11.b. compliant RF transceiver. The chip supports WiFi networks at 1 and 2 Mbps data rates. It is mounted on a chipKIT WiFi shield. The shield does not add any new feature to the radio chip (except for the on-PCB antenna) but offers easy connectivity to chipKIT Uno32 prototyping boards. The radio chip can be controlled by an external microcontroller via an SPI protocol compliant serial port.

(ii) The microcontroller (a PIC32MX320F128 processor) is located on a chipKIT Uno32 prototyping board. It runs at 80MHz and has 128K Flash and 16K SRAM memories. These features would allow us to use the Microchip Application Library TCP/IP stack functionality to control the radio-chip. The actual *RSSI* readings are reported to a local host using USB connectivity (also an inbuilt feature of PIC32MX320F microcontroller).

(iii) The host computer was a Lenovo ThinkPad laptop with an Intel(R) WiFi Link 1000 BGN NIC. Xirrus Wi-Fi Inspector and inSSIDer_3 software applications where alternatively used to record RSS readings from the NIC. On the other hand RSSI readings coming from the radio chip where stored on the host side using HyperTerminal. Linear curve fitting and other data analysis tasks where performed offline, in Excell.

The software running on PIC32 was written in C++ using MPIDE, a multiplatform integrated development that gives us access to TCP/IP functionality via two header files: DNETcK.h and DWIFIcK.h. The flowchart of this application is presented below:

```
1. perform a passive scan on all WiFi
   channels
2. wait for scan to complete
3. send (RSSI, MAC ADRS.) tuples for all
   detected AP to host computer
4. wait for one minute
5. go to step 1.
```

After a basic statistical data analysis (mean and variance), APs with high variance *RSSI* levels where discarded. For the other APs, the mean *RSSI* was recorded. These values where compared with *RSS* readings from the laptop's NIC. *RSS* data was retrieved from the NIC using two different software tools: Xirrus Wi-Fi Inspector and inSSIDer 3 on two separate occasions but on the same spot.

VI. EXPERIMENTAL RESULTS

The results of comparison between *RSSI* and *RSS* (retrieved with inSSIDer 3) are given graphically in figure 6.

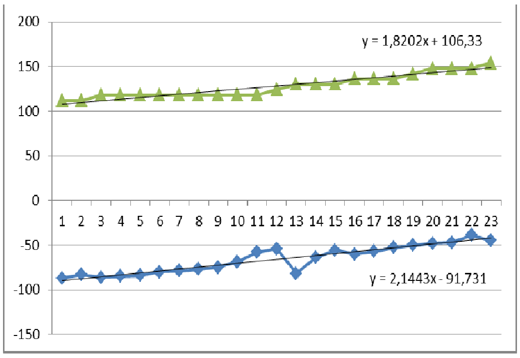


Fig. 6. RSSI (up, pozitive values) vs. RSS (down, negative values)

One can see in fig. 6 the linear trend of both data sets and the equations describing the result of linear data regression. Using these equations it is straightforward to prove that the relationship between *RSS* and *RSSI* is as given in (12).

$$RSS = 1.18 \cdot RSSI - 217 \qquad (12)$$

The results of comparison between *RSSI* and *RSS* (retrieved with Xirrus Wi-Fi Inspector) are given graphically in figure 7.

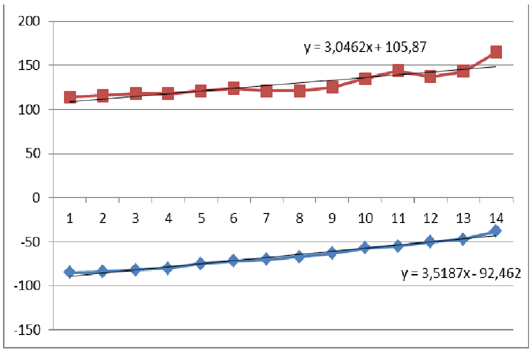


Fig. 7. RSSI (up, pozitive values) vs. RSS (down, negative values)

One can see in fig. 7 the linear trend of both data sets and the equations describing the result of linear data regression. Using these equations it is straightforward to prove that the relationship between *RSS* and *RSSI* is as given in (13).

$$RSS = 1.16 \cdot RSSI - 215 \qquad (13)$$

Comparing (12) and (13) we can see a very good match between the two equations and since we have no other reason to incline towards one of them we would suggest the mean of the two to be used:

$$RSS = 1.17 \cdot RSSI - 216 \qquad (14)$$

VII. CONCLUSION

In conclusion eq. (14) can be used for translating *RSSI* readings retrieved from MRF 24WBOMA radio into objective *RSS* readings expressed in *dBm*. This equation was derived experimentally but proofs the theoretical assumption expressed in eq. (9) i.e. the linear relationship between *RSS* and *RSSI*. In fact (14) is an instance of (9) for $\alpha=1.17$ and $\beta=-216$.

The range of valid *RSSI* readings (according to [11]) for this type of radios goes from 106 to 200. According to eq. (14) this would give an input power range of [-92dBm, 18dBm] which is consistent with the radio chip datasheet. In fact, in our experiment we never succeeded to obtain a *RSSI* value beyond *112* or above *166*. More over *RSSI* readings where relatively coarse grained, going from 112 to 166 with an increment of six from one level to the next (112, 118, 124, … and so on). According to (14), that means 7dBm distance between two adjacent *RSS* levels which is coarse but still better than those (only) six levels of Symbol radio transceivers.

Finnally table I summarizes our findings. As previously demonstrated Eq. (9) stands, if used with data provided by various radio chip vendors (in this paper data from Intel, Atheros, Symbol and Cisco datasheets where considered) and is consistent with experimental measurements to.

TABLE I

Radio chip	α	β	eq. (9)
INTEL	1	0	RSS = RSSI
ATHEROS	0	-95	RSS = RSSI-95
SYMBOL	1.67	-103	RSS = 1.67RSSI-103
CISCO	1.09	-113	RSS = 1.09RSSI-113
MRF24WB	1.17	-216	RSS = 1.17RSSI-216

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REFERENCES

[1] X., Luo et al., *Comparative evaluation of Received Signal-Strength Index (RSSI) based indoor localization techniques for construction jobsites*, Journal of Advanced Engineering Informatics (september 2010).

[2] Solomon Chan, Gunho Sohn, *Indoor localization using wi-fi based fingerprinting and trilateration techiques for lbs applications*, International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Vol. XXXVIII-4/C26, 7th International Conference on 3D Geoinformation, May 16-17, 2012, Quebec, Canada.

[3] T.-H. Lin, I.-H. Ng, S.-Y. Lau, K.-M. Chen, P. Huang, *A Microscopic Examination of an RSSI-Signature-Based Indoor Localization System*, The Fifth Workshop on Embedded Networked Sensors (HotEmNets 2008), Charlottesville, Virginia, 2008, pp. 2–6.

[4] P. Barsocchi, S. Lenzi, S. Chessa, *Self-Calibrating RSSI-based Indoor Localization with IEEE 802.15.4*, Instituto di Scienza e Tecnologie dell'Informazione del CNR, Pisa, Italy, 2008, pp. 1–6.

[5] P. Barsocchi, S. Lenzi, S. Chessa, G. Giunta, *A Novel Approach to Indoor RSSI Localization by Automatic Calibration of the Wireless Propagation Model*, Vehicular Technology Conference, 2009. VTC Spring 2009. IEEE 69th Barcelona, Spain, 2009, pp. 1–5.

[6] H.M. Khoury, V.R. Kamat, *Evaluation of position tracking technologies for user localization in indoor construction environments*, Automation in Construction 18 (2009) 444–457.

[7] O. Adewumi, K. Djouani, A. Kurien, *Performance Evaluation of RSSI Based Distance Measurement for Localization in Wireless Sensor Networks*, IEEE International Conference on Industrial Technology (ICIT), 2013.

[8] Yin Chen, Andreas Terzis, *On the Mechanisms and Efects of Calibrating RSSI Measurements for 802.15.4 Radios*, Lecture Notes in Computer Science Volume 5970, 2010, pp 256-27.

[9] Joe Bardwell, *Converting Signal Strength Percentage to dBm Values*, http://iutsa.unice.fr/~frati/Wireless/TD/Etude%20-%20Converting_Signal_Strength.pdf.

[10] Angelos Vlavianos et all *Assessing Link Quality in IEEE 802.11 Wireless Networks: Which is the Right Metric*? IEEE 19th International Symposium on Personal, Indoor and Mobile Radio Communications, 2008. PIMRC 2008.

[11] Microchip, *TCP/IP Stack Help*, Microchip Technology, 2012.

[12] P. Bahl, V.N. Padmanabhan, *RADAR: An In-Building RF-Based User Location and Tracking System*, in: Proceedings of IEEE Infocom 2000, Tel-Aviv, Israel, 2000, pp. 1–10.

[13] M. Sugano, T. Kawazoe, Y. Ohta, M. Murata, *Indoor Localization System Using RSSI Measurement of Wireless Sensor Network Based on ZigBee Standard*, The IASTED International Conference on Wireless Sensor Networks (WSN 2006) Banff, Canada, 2006.