Do RSSI values reliably map to RSS in a Localization system?

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***Abstract*—In recent years, research into localization systems has become more popular as the proliferation of Wireless Sensor Networks (WSNs) grows. Wireless Localization can refer to either an "Active" system which tracks a mobile transceiver, or "Passive" localization which tracks a transceiver free entity by measuring the changes it makes to the surrounding wireless environment. Recent work has seen both of these systems implemented with Received Signal Strength Indication (RSSI) values from transceivers. Many algorithms and channel models have been presented to increase the accuracy of a Received Signal Strength (RSS) based system. In this paper we experimentally check whether RSSI values map to the expected RSS values within an IEEE 802.15.4 network. Indoor experiments are repeated within an ideal outdoor environment, with multiple device platforms, to eliminate indoor multipath propagation as the cause for inconsistent behavior of RSSI. We identify 3 key issues with raw RSSI values and present either a possible solution or a mitigation strategy to reduce their effect. We conclude that using raw RSSI values is flawed, as the premise that they uniquely map to the distance between transceivers is incorrect. However they may be calibrated to increase their accuracy, and therefore viability.**

Keywords—Indoor Positioning System; Device Free Localization; Active Localization; Zigbee; Log Distance Path Loss Model

I. INTRODUCTION

The objective of this paper is to investigate whether raw Received Signal Strength Indication (RSSI) values reliably map to Received Signal Strength (RSS), for use in an Indoor Positioning System (IPS). In 802.15.4 networks, the RSSI is an 8 bit quantized value used to estimate the RSS within the bandwidth of the channel. We define raw RSS values as the values received directly from the 802.15.4 receiver, and will use this interchangeably with raw RSSI within this paper. It is often implemented in network code as two functions. The first function estimates the RSS within the channel itself (known as an ED scan)[1].The second function is used to estimate the RSS of a received packet, (given by the RSSI field) [1]. This paper will focus on the second function, power estimates of received packets. The 802.15.4 standard requires the raw RSSI value to linearly map (in decibels) to the true RSS and be accurate to ± 6 dB [1]. An IPS using RSSI can be implemented through either Device-free Localization (DfL) (Passive localization) [2] or Active localization [3, 4]. DfL is an emerging technology that can locate moving objects within an area surrounded by wireless nodes or radios. DfL works by creating a dense network of "linked pairs" as each radio surrounding the area of interest can transmit and receive wireless signals. When an object passes through the links, some of the signal is either absorbed or reflected by the object, thus resulting in less signal power (Received Signal Strength) reaching the destination node (radio). An image of where the power is being absorbed can be formed by analysing the loss along the "linked pairs", and thus a moving object's location can be detected [5]. Active tracking utilizes the same information (RSSI), but instead uses it as a form of wireless ranging where the tracked entity is in contact with several other nodes at any given time to contribute to the localization. RSSI Implementations of both methods rely on either known signal propagation behaviour or wireless ranging. Wireless ranging is based on the assumption that RSSI values will monotonically decrease as the separation between the transmitter and receiver increases [4, 6]. Signal propagation methods using RSSI are usually implemented by creating an offline fingerprint of the environment, also known as an RSSI map. After measuring the environment in an offline setting, these solutions assume that the variance caused by an entity to the wireless environment during live operation will be uniquely identifiable when compared to the stored map.

The goal of this paper is to check whether raw RSSI values correctly map to their RSS counterparts. This will be done by taking a common 802.15.4 Transmitter-Receiver (Tx-Rx) pair (TI CC2530) and checking whether RSSI values uniquely map to distance measurements in a monotonically decreasing function in both indoor and outdoor environments. The experiment is then replicated with another device platform (Microchip MRF24J40). This ensures that any propagation irregularities presented are both independent of indoor multipath effects and are platform independent. This will show whether the

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raw RSSI values of an 802.15.4 transceiver provide a good metric for implementing an IPS. Finally we will analyse the results and provide suggestions for improvements in an RSS based IPS implementation.

Here is how the rest of the paper is organized. Section II discusses previous implementations of a RSSI based localization system; Section III presents our system implementation; Section IV covers the implementation results and discussion; Section V concludes this paper.

II. LOCALIZATION METHODS

A. Active Tracking

Active tracking with RSSI works by using wireless ranging to estimate the distance between beacon nodes and the tracked node. Once data has been collected for at least 3 separate beacon links to the tracked node, wireless triangulation is used to estimate the coordinates of the tracked node. This is based on the assumption that the power of a received packet decreases as the distance between the transmitter and receiver increases. The model commonly chosen to represent this relationship is the Log-distance path loss model (LdPLM) [7] which can formally be expressed as:

$$P_{Rx_{dBm}} = P_{Tx_{dBm}} - PL_{d_0} - 10n\log_{10}\left(\frac{d}{d_0}\right) + X_\sigma \qquad (1)$$

Where $P_{Rx_{dBm}}$ is the power at the receiver in dBm, $P_{Tx_{dBm}}$ is the transmitted power in dBm, PL_{d_0} is the path loss in dB at a reference distance d_0, n is the path loss exponent and X_σ is a Gaussian random variable with zero mean.

Common applications will use the model to find distance estimates between the beacon transmitters and the receiver and either triangulate an approximate location, or more simplistically infer a region by checking which beacon(s) the receiver is closest to. Active tracking can also utilize a radio mapping approach where offline measurements are taken of the target in predetermined locations. During online operation, localization is inferred through similarity matching with the live RSSI vectors and the offline stored measurements.

B. Device-free Localization

Device-free Localization (DfL) is more difficult than Active tracking. Since the tracked entity doesn't carry a transceiver, the LdPLM cannot directly be used to calculate the entity's distance from a known fixed point. These types of systems exploit wireless signal propagation theory by understanding how RSS changes as either; Tx-Rx separation increases, or a Tx-Rx link has an entity pass through it. When an object blocks the line-of-sight (LOS) path between a transmitter and a receiver, assuming this is the dominant propagation path (ignoring multipath propagation), the relative path loss exponent will increase and therefore the received power at the receiver will be less, as some has been absorbed by the blocking entity. This behaviour can be utilized by fingerprinting methods. Fingerprinting creates a Radio Map similar to that mentioned in Active Tracking. The difference between the two is that Active tracking stores the RSSI vector between the static nodes and moving target. DfL stores the RSSI between all static nodes, whilst the target is located in a predetermined grid location. Fingerprinting based on a feature vector set works as follows. First, the localization area is divided into grids for offline measurements. The target moves into the first grid and remains stationary. RSSI values are collected between all static node links and are stored in the fingerprint database as sample vectors. This is repeated for all grid locations. When the system goes online, localization is inferred through similarity matching of the online RSSI vectors with the stored offline vectors.

A graphical approach to imaging the attenuation has been developed, known as Radio Tomographic Imaging (RTI)[5]. RTI measures the live variability of the RSSI measurements. By classifying the variability of the RSSI across multiple Tx-Rx links, an entity can be located at intersection points when it attenuates multiple links at the same time.

Both Active Tracking and Device-free Localization assume that there is a unique relationship between RSSI and distance. Active Tracking assumes that the received power at a receiver monotonically decreases (in ideal outdoor free space environments), as the separation between the transmitter and receiver increases. DfL assumes that an entity introduced to a measured area will introduce noticeable and explainable variability to received RSSI values. This is equivalent to the n (path loss exponent) changing between non-LOS links as the entity moves through the system for the LdPLM model.

III. IMPLEMENTATION

We set out to test whether raw RSSI values received from a common 802.15.4 transceiver do in fact map to the expected RSS values for a set distance based on the LdPLM. Initial measurements were taken with a pair of TI CC2530 transceivers. All measurements have been repeated with a second pair of CC2530 transceivers to ensure that all observed behaviour is platform specific rather than device specific. Measurements were also repeated with a pair of Microchip MRF24J40 transceivers to ensure that the results weren't platform specific. All measurements were performed with the radios operating with their respective highest transmission power. Since RSS based localization is generally considered for indoor applications, we took measurements from 1m – 10m transceiver separation at 1m intervals. This provides a good analog of the propagation behaviour within a home or small office environment. The experiments were undertaken in an open plan room, at the university, at night to minimize external interference. We also used ZigBee channel 26 as it has the best separation from Wi-Fi since Wi-Fi channels 12 and 13 are not utilized in New Zealand. All measurements were taken with the transceivers on stands at 1m above ground level. When a stand was moved, we ensured the front edge remained perpendicular to the line of Tx-Rx separation distances. This ensured that the transceiver antenna orientation remained constant for all distances. We were aware that the RSS value may deviate from a monotonically non-decreasing behaviour due to the presence of multipath propagation. This is usually accounted for in the LDPLM by the Gaussian random variable. The wavelength of 2.4 GHz ZigBee transmissions is approximately 0.125m. This means that a propagation path that is approximately 0.0625m longer than the main propagation path will arrive with an almost 180° phase change. Therefore 2.4GHz ZigBee signals are potentially very prone to multipath fading in indoor

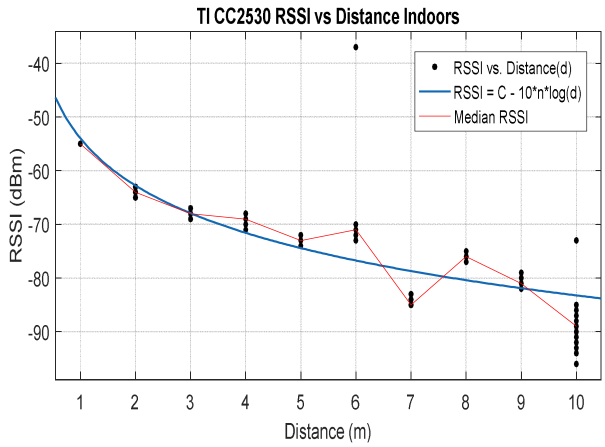

Figure 1 - RSSI values per distance within an indoor environment

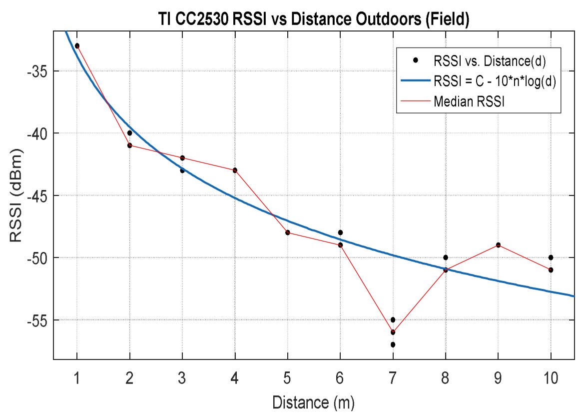

Figure 2 - RSSI values per distance within an outdoor environment (Field)

environments. Since this fading could be either constructive or destructive, there is the potential for large errors to be introduced when reading RSSI values indoors. There has been research undertaken that tries to measure RSSI vs Distance by minimizing potential interference [8, 9]. The problem is that it is unclear whether their results are caused by the spurious nature of RSSI, or by potential indoor multipath effects. Therefore to provide a best case, interference free, free space propagation test we repeated the experiment in 2 outdoor locations with multiple device platforms. The first outdoor location was in an empty stadium carpark and the second was in the middle of a large field. Both locations should have been completely free of 2.4GHz interference, and we confirmed with an android application Wi-Fi scanner that there were no Wi-Fi access points visible. We also ensured that for the carpark, there was no object located within 30m in any direction that could contribute reflective multipath components (excluding the ground itself). Within the field test scenario, there was no object located within 50m in any direction. When an experiment was started, a delay was used to allow the testing personnel to completely leave the testing environment before measurements began to ensure their physical presence did not affect the results. The experimental setup consisted of 3 CC2530 nodes and a laptop. The first node which was the transmitter would send a packet to the second node at a fixed distance away. The second node would measure the RSSI of the received packet and then forward the recorded RSSI information to a third node which was connected to a

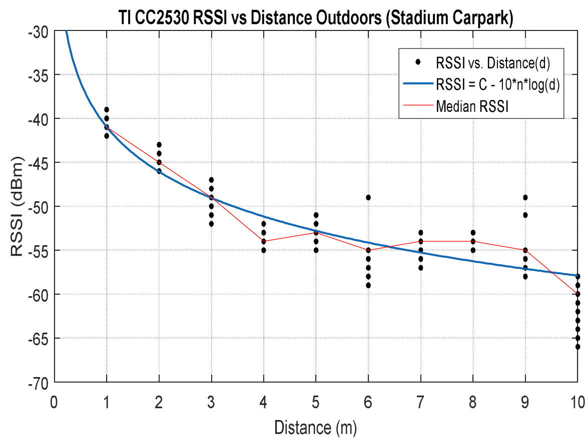

Figure 3 - RSSI values per distance within an outdoor environment (Carpark)

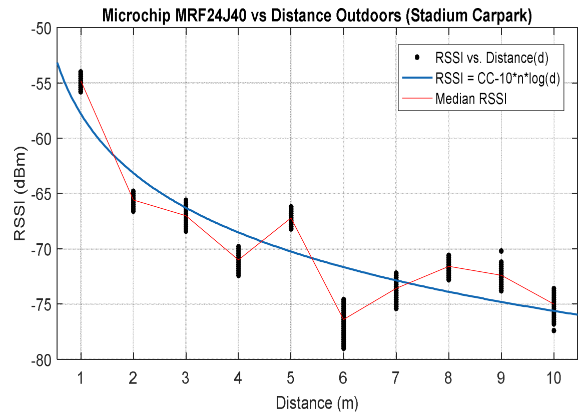

Figure 4- RSSI values per distance within an outdoor environment (Carpark)

laptop collecting all data. This was done to remove the data-logging laptop from the Tx-Rx pair to ensure that no artefact was introduced from potential reflective signal components off the laptop itself. At every 1m distance interval, 5000 measurements were taken to ensure that the measurements were resilient to fast fading. The antenna orientation was also kept constant with every set of measurements to prevent any errors due to anisotropic propagation (even though the antenna was omnidirectional).

IV. Results and Discussion

For ease of use, when fitting a curve to the raw RSSI results, we simplified (1) to:

$$P_{Rx_{dBm}} = C - 10n\log_{10}\left(\frac{d}{d_0}\right) \qquad (2)$$

where C represents the transmitted power in dBm minus the path loss in dB as calculated at a reference d_0 of 1m, and the guassian zero mean random variable. Figures 1, 2 and 3 all show the fitted LdPLM as compared to median RSSI values per location. Median RSSI was chosen over mean RSSI as it is more resilient to influence from outliers since our sample size was large. To check that the behaviour of the raw RSSI fluctuations wasn't platform specific, we also tested with the Microchip MRF24J40 transceiver. We noticed that the variation of raw RSSI values was larger on the MRF24J40 than it was on the CC2350 platform. However the collected data were consistent with the

CC2530 results. The CC2530 maps the register RSSI value to a RSSI dBm estimation by subtracting a constant dB offset. This means that the RSSI (dBm) is always an integer like the quantized RSSI register (which has a step size of 1dB). The MRF24J40 includes both a scaling factor and an offset when converting from the RSSI register to dBm. This means the quantized register has an equivalent stepsize of 0.2dB*. Therefore Figure 4 contains fractional dBm values whilst Figures 1, 2 and 3 are all whole numbers. There are three causes for concern that our measurements raise when considering the use of raw RSSI values for localization purposes outlined as below.

A. *Uniqueness Error*

We define an RSSI value as unique, if it only maps to 1 corresponding Tx-Rx separation distance. The data shows that for both indoor and outdoor (ideal) environments, there exist regions where a raw RSSI value does not map uniquely to a distance value. This can be seen most clearly in Figure 3 where distances d_4, d_7 and d_8 all have the same median RSSI value. This appears again with d_6 and d_9, and in Figure 2 with d_8 and d_{10}. Since all experiments were instigated with interference minimization in mind, we conclude that this behaviour is most likely due to intrinsic hardware peculiarities rather than an multipath fading skewing the readings. It should also be noted that the RSSI values received are well within the acceptable mid-range, and therefore it is not an issue relating to possible erroneous readings near the transceiver sensitivity threshold. This is also backed by our measurements from within a field which show very low RSSI variation with some distances, even maintaining the same RSSI reading across all 5000 samples (d_1, d_4, d_5 and d_9). This suggests that the effect of multipath propagation and environmental noise is either minimal, or remained relatively constant over the duration of the testing. This behaviour can also be clearly seen on the Grenoble and Strasbourg SensLAB platforms, at set distances, which utilize 256 TI CC1101 radios respectively [8]. It has also been seen to occur on the popular TI CC2420 [9]. Lui et al experience this behaviour with Wi-Fi propagation in both indoor and outdoor environments across multiple device platforms [10].

This is a significant issue that would affect both Active Localization and DfL. For an Active Localization system utilizing wireless ranging, this means that for any singular link, there will be raw RSSI values that map to multiple possible "actual" distances. This is problematic as the system could appear to be working correctly for the majority of the time, but could experience errors whenever a roaming node returns an RSSI link value which could correlate to multiple physical locations. A different issue arises due to the non-unique mapping within a DfL environment. DfL systems work by measuring the environmental change in RSS when an entity enters the system. The uniqueness error means an entity attenuating a Tx-Rx pair by varying amounts could potentially return the same RSSI values. The is problematic for both variance and mean based RSSI DfL systems as the system will return erroneous readings when the RSSI values transition between unique and non-unique regions. This adds complexity as Tx-Rx links have to be weighted not only by their own variance, but also other local link variances, and by whether the returned RSSI values themselves are unique.

There has been some research done that suggests that radios may not have necessarily have a linear relationship between raw RSSI values and RSS for all regions [11]. Chen and Terzis experimentally verify that non-linarites are platform specific. Therefore if the non-linear regions are known for the implemented radio, they can be accounted for accordingly. This is done by understanding the following relationship for RSSI given by Chen and Terzis[11]:

$$RSSI_{RX_{dBm}} = RSSI_{\,TX_{dBm}} - PL_{dB} \qquad (3)$$

where $RSSI_{RX}$ is the received power, $RSSI_{TX}$ is the transmitted power and *PL* is the path loss. When an RSSI value is read and maps to a known non-linear region, the receiver asks the transmitter to retransmit at a different known power level. This is repeated until the receiver receives a RSSI value from a known linear region. This is then used with the known transmitted power level to calculate the *PL* factor. Since the *PL* is constant irrespective of the transmission power, this can be used alongside the known original transmission power to calculate an appropriate received RSSI value (calibrated). This calibrated value will result in decreased RSSI variance when measuring between two stationary locations and will change the mean / median of known erroneous non-linear points. This could potentially reduce the *uniqueness error* caused by multiple consecutive RSSI values falling within a flat non-linear region, as they will now have unique values.

B. *Deviation Error*

We refer to a RSSI value as a potential deviation error when the median (and / or mean) of the RSSI at any set distance lies significantly away from RSSI values either side of it. This is most visible for d_7 in both Figure 1 and Figure 2 which we term as *deviation locations*. When propagation peculiarities are seen in indoor environments, there are often assumed to be due to multipath behaviour. Since the deviation error seen indoors in Figure 1 is also apparent in outdoors in Figure 2, multipath propagation is unlikely to be the cause. This again suggests a hardware specific peculiarity that should be considered whenever using RSSI values. This behaviour has also been seen in RSSI vs Distance measurements taken on the popular TI CC2420 [12] and in a variety of Wi-Fi platforms [10].

For an Active system utilizing ranging, this phenomenon would introduce large localization errors at the *deviation locations* if raw, uncalibrated RSSI values were used within a range based estimation system. For a variance based DfL system, larger variation within links would be seen when an RSSI link value was received which had the same value as a *deviation location* from a standard RSSI vs Distance plot. As long as the weighting was not placed solely on the magnitude of the RSSI variance and rather on other known spatial properties, this wouldn't cause large localization errors, but it needs to be accounted for. Whilst the underlying erroneous raw RSSI values are hard to correct in this scenario, preventative measures can be taken to mitigate their effect. By implementing sanity checks and using a probabilistic movement approach (by ensuring any localized entity must travel through a surrounding region to reach a far location), pathing can be established [13]. This will improve the

* The MRF24J40 is based on the UZ2400. The UZ2400 datasheet provides a register to dBm RSSI conversion whilst the MRF24J40 does not. Thus it is assumed the MRF24J40 follows the same mapping.

accuracy in an Active ranging system since walking through a *deviated location* will not result in a predicted location set far away from the last known location. This error can also be minimized by utilizing more sensors, thus increasing the system resolution and making it easier to filter out suspected erroneous raw RSSI values. Finally, Zanella and Bardella show that the accuracy of range based localization can be improved by averaging the RSSI across multiple channels [14]. They show that this approach reduces the RSSI variance at a location, which could fix the problem of *deviation locations* if they prove to be a channel specific error. Though this reduces the effect of indoor multipath, it would not fix non-injunctive regions. Their results show large improvements on the raw RSSI values, but Uniqueness Error and Deviation Error still appear to be present.

C. Asymmetrical Error

The 802.15.4 standard requires the RSSI dBm value to be within ±6dB of the true value. The CC2530 claims to meet ±4dB of the true value. A 12dB swing is very large considering that ideal free space propagation assumes 6dB loss per octave. We did not have the equipment to accurately read the received RSS of a node (as this would require an accurate spectrum analyser). But we did notice that the raw RSSI within a link was not symmetrical, i.e. the RSSI value read from a packet at node B, sent from node A was not equal to the RSSI read at node A, from a packet sent by node B. This behaviour was also seen in a large scale indoor environment implementing a system based on TI CC1101 radios [8]. Through experimentation we found that though the links were asymmetrical, they were separated by a linear dB offset (O_{dB}). Thus we propose the following formula:

$$RSSI_{\underset{\rightarrow dBm}{AB}} = RSSI_{\underset{\rightarrow dBm}{BA}} + O_{dB} = RSS_{TRUE_{dBm}} + DO_{dB} \quad (4)$$

This shows that whilst any CC2530 device offset (DO_{dB}) will be within 4dB of the true value, it doesn't mean that all devices from the same product line will have the same offset (otherwise all links would be symmetrical in an ideal environment for identical radios). In our testing, the dB offset (O_{dB}) between 2 nodes, appears to be constant across the range (1-10m).

The results show that the *Asymmetrical Error* will have little effect for variance based DfL systems, as the term cancels out when taking the difference between two RSSI measurements, measured from the same node. It will however have a large effect on range based Active Localization systems. This finding means that either each link needs to be calibrated with its own model specific coefficients, or the raw RSSI values need to be pre-calibrated to the same mapping, before use in a range based system. This can be done by choosing a reference node, and calibrating all offsets to be equal to the chosen node. Care needs to be taken as even after calibration, it may not be advisable to deploy a single model (such as LdPLM) over the global system. If the system is implemented within an indoor environment, the path loss exponent could vary due to walls, and multipath propagation will have an effect on the system. Therefore it may still be advisable to use multiple ranging propagation models for various links in a system where propagation path loss could vary greatly between different nodal links.

V. Conclusion

As we have shown, raw RSSI values do not follow a monotonically decreasing function. We have also shown that propagation peculiarities still occur in ideal outdoor environments and therefore are not due to multipath fading effects. This is significant, as it shows that raw RSSI values do not provide a consistently accurate measure of true RSS in 802.15.4 devices. Three major concerns were raised and either a solution or mitigation strategy was proposed. We conclude that raw RSSI should not be used for localization purposes, but it may be possible to calibrate the raw RSSI values to provide a more usable localization metric. Users need to be wary of the limitations of device reported raw RSSI values, and address them accordingly to increase the accuracy of RSSI values.

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