Finding NEMO: On the Accuracy of Inferring Location in IEEE 802.15.4 Networks

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ABSTRACT

As embedded networked sensing devices become increasingly commonplace, more and more applications are being discovered, researched, and realised using them. These application domains in turn place new requirements on the capabilities of the embedded devices and associated communications technologies.

By introducing a novel domain for wireless sensor devices, this paper motivates the need for accurate proximity information between embedded networked devices and goes on to document a set of detailed experimental results and analysis, obtained from an IEEE 802.15.4 test bed. These results are compared to other similar studies in the field. Factors found to affect performance are highlighted, and techniques to improve performance are discussed, compared, and contrasted. Finally, conclusions are drawn as to the accuracy which can be obtained from IEEE 802.15.4 devices, and the associated costs and implications.

Categories and Subject Descriptors

C.3 [**Special-Purpose and Application-Based Systems**]: Real-time and embedded systems – *Proximity detection and measurement.* C.2.1 **[Network Architecture and Design]** Wireless Communication – IEEE *802.14.4, sensor networks, personal area communications*

General Terms

Measurement, Performance, Design, Experimentation.

Keywords

IEEE 802.15.4, radio, RF, location, localization, proximity, range finding, RSSI, packet loss, LNA gain, attenuation.

1. INTRODUCTION

Accurately determining the location of mobile / embedded devices has been of great interest to the networking field in recent years. Predominantly, this location information is used within the wireless sensor network (WSN) research area to enable the mapping of sensor nodes within a sensor field and also to aid the routing and forwarding of information through ad hoc sensor networks by utilising techniques such as directed diffusion and location aware routing[1][4][5][7]. However, there are also other (more application driven), needs for location information within WSNs, which have different requirements to these more traditional uses.

The ongoing NEMO[1] research project, at Lancaster University, is investigating how low cost embedded wireless devices can be used to *improve the health and safety of field workers*. Many workers in modern society experience hazardous environments as part of their everyday lives. (Some work with noxious or dangerous chemicals; others operate heavy machinery capable of inflicting harm to themselves or others; or are vulnerable to potentially hazardous environments, such as road-workers on busy motorways.) Health and safety (H&S) regulations are often put into place by employers or government bodies to minimise the risks associated with these environments. H&S rules state procedures and limitations associated with work processes. The key aim of the NEMO project is to augment artefacts in the workplace such as tools, vehicles and workers themselves with intelligent sensor devices, which are capable of collecting and analysing data from their environment to detect (and potentially correct), violations in H&S regulation in the field. Given the lack of fixed infrastructure present around most fieldworkers (consider construction sites, highways, storage yards), a distributed, ad hoc approach is adopted in investigating this problem.

By way of example, consider one motivating scenario. It is estimated that 288,000 people in the UK alone suffer from a long term medical condition known as vibration white finger (VWF) [12], a complaint which ultimately results in the total loss of feeling in the fingers. It is brought about through prolonged exposure to hand-arm vibration, a result of using heavy vibrating machinery such as pneumatic drills, etc. Since the discovery of VWF, H&S regulations have been introduced which limit a worker's daily vibration exposure. By augmenting tools with sensor devices, the vibration produced by a tool can be measured in the field and a worker's computing device can be used to record and process cumulative exposure and keep his/her exposure inline with the regulations.

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The above is just one example; there are countless such regulations, many of which rely on the concept of *close quarters proximity*. For the VWF example, the proximity between a tool and a worker gives a strong hint to which worker is operating which tool. Other regulations state that certain work should only be carried out when more than one worker is present – requiring knowledge of proximity between workers. As a further example, some regulations govern the storage of objects which may also require knowledge of the proximity between such objects, for example disallowing the storing of explosive materials next to heat generating appliances.

To enable these applications, there is a need to accurately, reliably, and inexpensively detect to centimetre accuracy the distance between devices *but only within a small, fixed distance of one another – typically a few metres*.

Whilst proximity can be achieved through custom solutions (such as RFID), it is beneficial to minimise the complexity of embedded devices where possible in order to reduce cost, ease of deployment, and promote energy efficiency. Therefore, this investigation is to discover how accurately, *in practice,* proximity can be inferred from the RF characteristics of modern data radios, such as IEEE 802.15.4. More specifically, ascertain how accurately, and at what cost, close quarters proximity can be inferred between two wireless devices using only the RF channel; and the best technique / metric to measure proximity.

In this paper, both the RSSI and packet loss metrics are adopted and their effectiveness for close quarters proximity measurements in IEEE 802.15.4 networks is compared and contrasted. It is shown that the choice and manipulation of the radio parameters can show significant effect upon the accuracy of proximity measurements.

2. RELATED WORK

Analysing information gathered from wireless network interfaces to estimate ranging / location information has been the subject of much research in recent years. Since the seminal works undertaken by Hightower et al. [3], many researchers have advocated the use of received signal strength indication (RSSI) to estimate the distance between a transmitter and a receiver. Others use packet loss as a metric, preferring to 'flood' a network with packets, and performing distance estimation based upon which packets are accurately received.

Marrying RSSI with locality has become somewhat of a modern day alchemy. The benefits of a ranging technique based purely upon RSSI are clear – reduced power consumption, size, and cost. However, numerous studies have proven that the accuracy of RSSI to be highly questionable. Absorption, reflection, refraction, and multipath propagation highly influence the properties of electromagnetic waves. Thus, when monitoring the 'strength' of that wave, it may appear stronger/weaker than if it had propagated through a vacuum in a direct line. Existing research shows us that accurate range estimation / localisation requires accurate models of the environment (as is used in the RADAR system [2]). However, such knowledge is rarely available "in the field", as with most NEMO scenarios. Furthermore, few studies have reported results for, and none have focussed upon, the gathering of accurate proximity data over short transmission ranges.

Some authors have reported high degrees of accuracy with packet loss based metrics [8]; such approaches are inherently expensive, in terms of energy efficiency and channel utilisation and, moreover, the results from the experiments discussed in this paper show this to be a poor metric for IEEE 802.15.4.

Proximity may be detected by limiting the transmission range of a radio by artificially altering properties of its antenna [10]. Such an approach, however, can have a serious detriment to data throughput rates.

A number of general purpose localisation solutions also exist, such as GPS, Galileo, RFID, Landmarc [6], Active Bat, and Cricket [13], and although relevant, do not apply themselves well to use in the field domain due to heavy reliance on infrastructure.

3. PROXIMITY MEASUREMENT USING IEEE 802.15.4

IEEE 802.15.4 [11] is a ratified international standard that has been specifically designed as a solution for ultra low powered applications; it exhibits low complexity to reduce production cost and provides prolonged life from a single battery cell. IEEE 802.15.4 is emerging as *the* de facto standard for wireless control networks (as is indicated through its uptake by the Zigbee alliance and adoption by the many popular motes platforms), and (typically) operates in the 2.4GHz ISM band. Because of its widespread use, determining locality using indicators from the IEEE 802.15.4 radio channel is a tantalising prospect for future WSN deployment.

Through a series of laboratory based experiments, the effects of distance, output power, and input gain on RSSI and packet loss were measured and recorded. The following sections outline the hardware used, experiments undertaken, and results attained.

3.1 Hardware Overview

A custom control board was constructed for the purpose of these experiments, see figure 1. The hardware features: a Chipcon CC2420EM transceiver module, driven by an 8-bit PIC 18F2420 microcontroller via SPI, and also features an RS232 control and diagnostics interface.

The CC2420 offers a mechanism for selecting the transmission output power of the radio programmatically. Thirty-two individual power levels are specified with 31 being the highest power output and 0 the lowest. The CC2420 also utilises a variable gain low noise amplifier (LNA) which, like most radios, intelligently amplifies received transmissions and therefore offers low strength signals an improved chance of being received correctly.

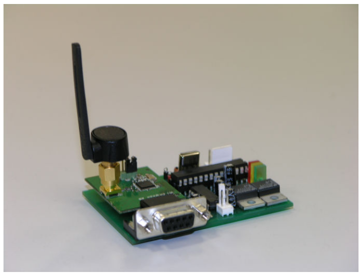

Figure 1 - IEEE 802.15.4 Proximity Evaluation Board

Custom software was also developed to achieve low level access to radio functionality, including output power control, RSSI detection, and receiver gain control**.**

3.2 Experiment Overviews

For these experiments, two nodes were configured as a designated transmitter or receiver.

The transmitter sends MAC frames directly to the receiver, at varying output power levels. The power level at which the packet is sent is also encoded into the frame payload, where it can be later extracted for analysis. These frames are received by the receiver node, which is connected to a host PC via the RS232 serial line. The receiver node delivers statistics concerning received frames (RSSI information, packet count, and transmitted power level), allowing an application executing on the PC to timestamp, log, and process this information as it arrives.

The receiver is positioned in a fixed location and the transmitter is suspended in free space, as illustrated in Figure 2 below. The distance between the transmitter and receiver is controlled and increased from 10cm to 400cm in increments of 10cm. At each location, the transmitter node transmits 255 frames – for each of the 32 selectable power levels – and the received data logged by the host PC.

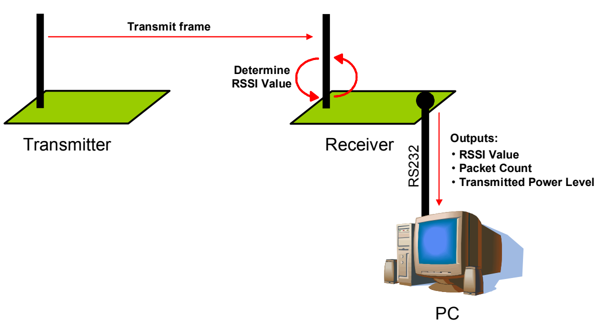

Figure 2 - Experiment Configuration

3.3 Baseline IEEE 802.15.4

As a first trial, a baseline study was conducted of the IEEE 802.15.4 hardware in its factory default configuration. Figure 3 shows the mean RSSI detected at the receiver – for each of the 255 frames – in the range of 20 to 200cm. For clarity, a representative subset of the total 31 power levels is shown: levels 10, 20, and 31.

As can be seen from Figure 3, although a weak long term relationship between distance and RSSI can be observed, the trend between RSSI and distance is elusive. This further corroborates the findings of other related works [8] [9], in that the observed RSSI data does not correlate directly with the exponential decay model as the theory would dictate. However, a trend is clearly visible, repeatable, and not random in nature, as can be seen by comparing the samples for different power levels.

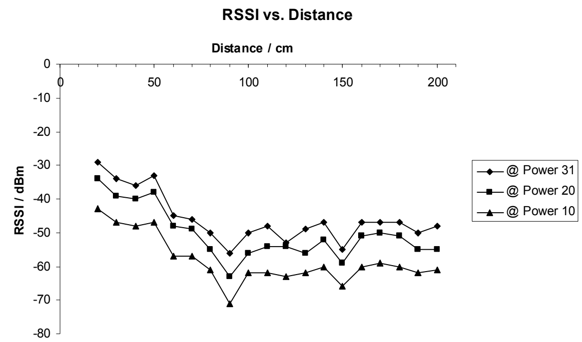

Figure 3 – RSSI between two IEEE 802.15.4 nodes with factory default setting. Standard deviation: mean 10.32dBm, max 14.42dBm, min 6.61dBm

Effective packet loss over the wireless link was also recorded during the same experiment run. Figure 4 shows a plot of packet loss against distance for a subset of the 32 power levels. Only power levels 0-2 are shown for clarity – the higher levels experienced no packet loss. As can be seen from the diagram, again, no clear trend can be observed.

It can be concluded, from these tests, that even coarse grained proximity cannot be determined from packet loss nor RSSI measurement for default configurations.

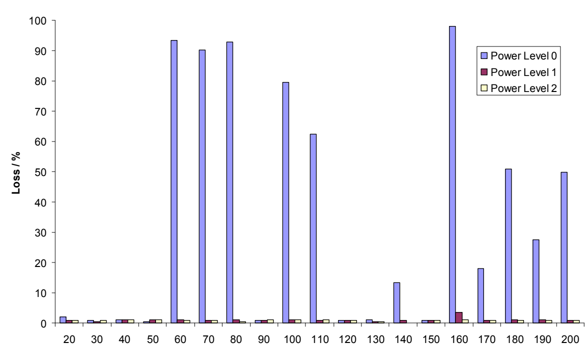

Figure 4 – Packet loss observed between two IEEE 802.15.4 nodes with factory default setting.

3.4 Effects of Transmitter Attenuation

IEEE 802.15.4 implementations, such as that described here, provide an approximate range of up to 80 metres dependent upon chosen transmitter power level and the surrounding environmental conditions. By attenuating the output of the IEEE 802.15.4 transmitter, the transmission range can be effectively reduced, without losing the resolution of control given through the CC2420 power control interface. For example, if the transmitter were attenuated to 1/10th of its normal output power, the 32 power levels increase in granularity by a factor of ten.

To test the effectiveness of this concept, a 9db attenuator (linear attenuation of approximately 8:1) was added to the transmitter and the experiments were repeated. The results of the RSSI experiments can be seen in Figure 5. Note the drop in RSSI level compared to the unmodified case in Figure 3; this is encouraging, however, there is still no clear trend which is useable in general case to determine location from RSSI information.

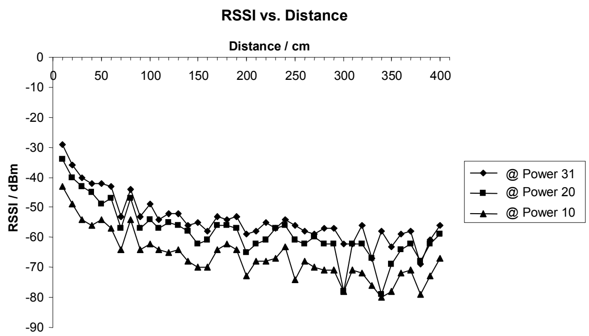

Figure 5 – RSSI between two IEEE 802.15.4 nodes with 9db attenuation on transmitter. Standard deviation: mean 8.16dBm, max 14.66dBm, min 6.11dBm

Figure 6 shows the packet loss statistics for the same trial with the attenuator added. Compared to figure 4, it is clear that some coarse grained location information could be inferred from packet loss using this technique. For example, the increase in packet loss for power level 0 at 30cm. Even under these controlled conditions, when power levels 1 & 2 are considered at distances between 40 and 100cms the unreliability of this approach is revealed.

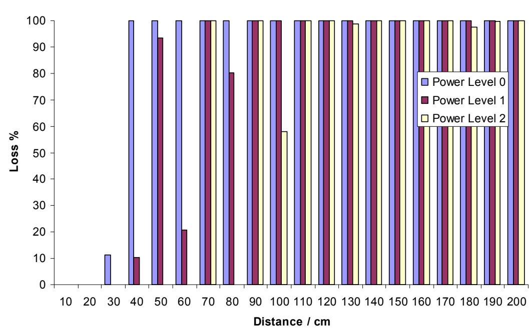

Figure 6 – Packet loss observed between two IEEE 802.15.4 nodes with 9db attenuation on transmitter.

3.5 Effects of LNA Gain

Most sophisticated radio receivers contain variable gain low noise amplifiers in the receivers. The purpose of such amplifiers is to reactively boost the received input signal to a more 'workable' level. This stage is typically performed before any other on the radio – including RSSI detection. So, while this provides great benefit for improved data reception, it only serves to add error into a system which uses RSSI to infer location information.

To investigate the effects of this, a further run of the experiment was carried out, with the gain of the receiver's LNA set to a low, fixed, level, rather than the default variable gain. The results of this test are shown in figure 7. In keeping with the previous results, RSSI is shown against distance for the same three power levels: 10, 20, and 31.

Of greatest interest in figure 7 are those values taken at a distance of less than approximately 100cms. When compared to the previous RSSI plots, it is clear that 'pinning' the receiver gain results in a far more linear and predictable trend at close quarters. More specifically, these results indicate the accuracy of 10cm would be quite feasible at ranges up to 1m; thus, rendering this technique viable as a means of proximity detection in that range.

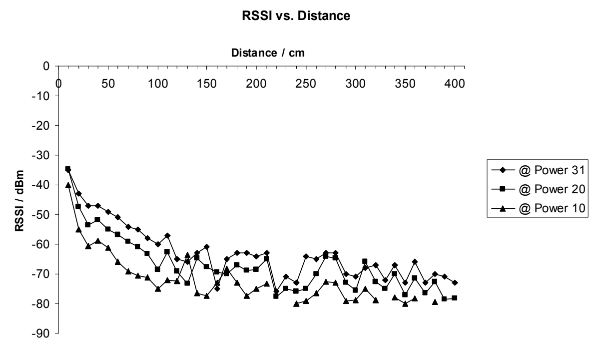

Figure 7 – RSSI between two IEEE 802.15.4 nodes with 9db attenuation on transmitter and fixed LNA gain on receiver. Std. dev.: mean 4.52dBm, max 7.06dBm, min 2.20dBm

The CC2420 offers four settings for the LNA gain: 'Low', 'Medium', 'High', and 'Variable'; figure 8 shows the effect of these various settings on the reported RSSI values.

Each point in figure 8 is taken from the mean RSSI value of a sample of 255 frames which have been transmitted at a fixed output power (level 10).

In figure 8, the effect of LNA on RSSI is clear to see: the high, medium, and low settings, initially, occupying clearly separated levels in the graph. The lowest LNA setting exhibits the stablest trend while medium, high, and variable appear more erratic.

The trend shown in figure 8 for the low gain values is not an absolute match to that in figure 7. It is believed that this may be attributed to the different method in which the results shown in figure 8 were obtained, vs. those in figure 7; those in figure 8 may have been influenced greater by the presence of a person.

Although a comparison with the LNA switched off completely would have been desirable no such mode is supported on the CC2420.

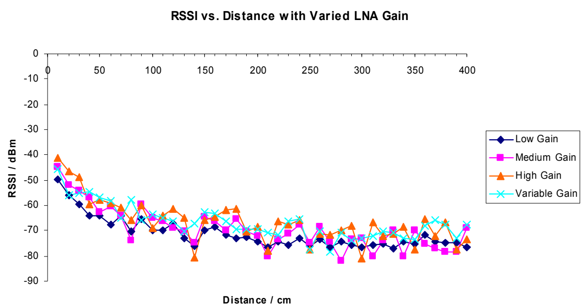

Figure 8 – RSSI between two IEEE 802.15.4 nodes with 9dB attenuation on transmitter and varied LNA gain on receiver.
Low std. dev.: mean 1.29dBm, max 2.72dBm, min 0.34dBm
Med. std. dev.: mean 2.27dBm, max 4.54dBm, min 0.23dBm
High std. dev.: mean 2.57dBm, max 6.65dBm, min 0.70dBm
Var. std. dev.: mean 2.60dBm, max 5.51dBm, min 0.77dBm

4. CONCLUSIONS

There is a clear need for accurate, low cost, and low overhead close quarters proximity information in emerging WSN domains – for example, the health and safety scenario described earlier. Based upon the development of a real world test bed and a set of experimental trials, the accuracy that can be achieved with IEEE 802.15.4 radios has been investigated using RSSI and packet loss. Furthermore, the effects of variable transmission power level, transmission attenuators, and fixed/variable gain receiver LNAs has also been investigated

In conclusion, it has been discovered that the frequently documented technique of utilising packet loss as a metric for proximity is a very poor choice for IEEE 802.15.4 networks; due to its high tolerance to noise. Also, it has been shown that the often overlooked parameter of receiver gain has a highly significant effect upon the effectiveness of RSSI based techniques. Furthermore, it has been shown conclusively (through experimentation), that close quarters proximity detection can be achieved using this technology down to an accuracy of 10 centimetres, thus enabling domains such as the health and safety scenario, without the need for additional equipment on the embedded device.

Since many new radio devices offer multiple antennas and software control of the received LNA gain (as with the CC2420), such proximity detection can be enabled without detriment to an 802.15.4 network as a whole. (Such devices can switch from factory default "communications" mode to the "proximity" mode in a matter of milliseconds.)

The experiments reported here involved just two nodes. Other works in this field have indicated that when additional nodes are also transmitting in the channel, that this may have an effect on the recorded RSSI. Further work would be required to test this phenomenon.

As highlighted in [9], the effect of the orientation and the placement of sensors (specifically regarding IEEE 802.15.4 networks) on RSSI is a marked one. While the effect of the orientation of the antennas was not investigated, their orientation and position was not stringently governed during these investigations and as such may have introduced slight errors into the results.

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