An Experimental Study on IEEE 802.15.4 Multichannel Transmission to Improve RSSI–Based Service Performance

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Abstract. In Wireless Sensor Networks (WSNs) the majority of the devices provide access to the Received Signal Strength Indicator (RSSI), which has been used as a means to enable different services and applications like localization, geographic routing and link quality estimation. Notwithstanding the popularity of using RSSI for localization, academic research showed that RSSI-based distance estimate is rather unreliable due to the random attenuation experienced by the radio signals, as the multipath fading. In this paper we propose a simple way to improve the RSSI reliability, averaging samples collected at different frequencies by a CC2420 radio, which implements the IEEE 802.15.4 standard, both in real indoor and outdoor scenarios. For this purpose, we introduce a simple communication protocol to coordinate data exchange between nodes, that exploits multichannel transmission in order to mitigate the multipath effect that hampers ranging estimation as well as wireless communication.

1 Introduction and Related Work

Ever since the beginning of radio communication, linking the communication distance to the received signal power in a reliable way has been a hot research topic. Solving this issue would open the path for accurate localization applications [1], precise geographic routing [7], trustful self-driven robots [8] and a whole set of other context–aware systems [9].

The availability of a Received Signal Strength Indicator (RSSI) in most of commercial off-the-shelf radio transceivers has promoted the design of several RSSI-based ranging techniques that, however, suffer two major drawbacks. On the one hand, inferring the transmitter-receiver distance from the received signal strength requires a rather accurate channel propagation model [12,18]. On the other hand, the relation between distance and received signal power is very noisy due to the random attenuation phenomena that affect the radio signals, as multipath fading and shadowing [19,15].

In this paper we address these two issues in the case of radio systems based on the common IEEE 802.15.4 standard. We observe that many works focus

P.J. Marron et al. (Eds.): REALWSN 2010, LNCS 6511, pp. 154–161, 2010.

on IEEE 802.15.4 channel characteristics [18] and investigate the feasibility of using RSSI measures for ranging purposes [16]. In general, results show that RSSI-based ranging is quite poor, in particular in indoor environments [17], so that accurate localization is possible only using large number of RSSI samples [8] and/or sophisticated filtering processes to reduce the localization error [10,11].

However, to the authors' knowledge, no previous work has yet considered the possibility of exploiting the frequency diversity provided by the standard to enhance the ranging performance. In this paper, we advocate that the RSSI-based ranging accuracy can be significantly improved by considering a more accurate channel propagation model and a slightly more sophisticated communication protocol that enables the collection of RSSI samples on different frequency channels. More specifically, we first propose an Extreme Value Distribution model for the received power, which fits our empirical data better than the most common Gaussian model, both in indoor and outdoor scenarios. Second, we prove that averaging the RSSI samples collected at different carrier frequencies will mitigate the multipath fading effect, thus potentially improving the RSSI-based distance estimate at a price of a limited increase in the communication protocol complexity.

2 Channel Characterization

An extremely accurate channel model would require perfect knowledge of the environment. Clearly, such a model would lack in generality and reusability. Therefore, it is generally preferable to consider more general models that can fit a much wider set of scenarios, though with lower accuracy. A very common radio channel model that binds the received power P_{rx} to the distance d between the transmitter and the receiver is the following:

$$P_{rx} \text{ dBm} = P_{tx} \text{ dBm} + K \text{ dB} - 10\eta \log_{10}\left(\frac{d}{d_0}\right) + \Psi \,, \tag{1}$$

where P_{tx} is the transmitted power in dBm, K is a unitless constant that depends on the enviroment, d_0 is the reference distance to be in far field conditions, η is the path loss coefficient and Ψ is a random variable that takes into account fading effects. Characterizing these parameters to the specific environment makes it possible to use the same model in different scenarios.

For instance, in a free–space environment we typically have $\eta = 2$ and K dB $= 20 \log_{10} \frac{\lambda}{4\pi d_0}$, with λ the wavelength at the carrier frequency. For other common environments (in office, open space, urban and so on), K and η can be retrieved from the literature [6] or, alternatively, jointly determined minimizing the mean square error (MSE) between the model and the empirical measurements.

The characterization of the random term Ψ is, instead, more arguable. A common practice is to model Ψ as a Gaussian random variable, with zero mean and standard deviation σ_{ψ}. In this paper we advocate that, for the technology and the environments considered in this study, the model of Ψ that statistically best fits with our empirical data is the Extreme Value random variable. This model arises if we consider a received signal composed of clusters of multipath waves propagating in a non-homogeneous environment. In this case, the envelope of the received signal turns out to be Weibull distributed [13,14], with probability density function (pdf)

$$f_Z(z) = (\beta/\Omega^\beta) z^{\beta-1} e^{-(z/\Omega)^\beta} ,$$

where the power parameter β expresses the fading severity. In dB scale, the received signal power $P_{rx} = 10\eta \log_{10}(Z)$ turns out to have an Extreme Value distribution $f_X(x)$ with pdf

$$f_{P_{rx}}(x) = \frac{A}{\sigma} e^{(Ax-\mu)/\sigma} e^{-e^{(Ax-\mu)/\sigma}}$$

where $A = \frac{\ln 10}{10\eta}$, $\mu = \ln(\Omega)$ and $\sigma = 1/\beta$. As a result, the term Ψ in (1) is also described by an Extreme Value distribution with pdf

$$f_\Psi(x) = \beta A M e^{\beta A x} e^{-Me^{\beta A x}} = \sigma_\psi^{-1} e^{(x-\mu_\psi)/\sigma_\psi} e^{-e^{(x-\mu_\psi)/\sigma_\psi}} \tag{2}$$

with parameters $\sigma_\psi = (A\beta)^{-1}$ and $\mu_\psi = -(A\beta)^{-1} \ln M$, $M = \left(\frac{P_r^{1/\eta}}{\Omega}\right)^\beta$, and P_r denoting the mean received power (in mW).

The Maximum Likelihood estimation for d based on (1), is given by

$$\hat{d} = d_0 10^{\frac{P_{tx}+K-P_{rx}+\mu_\psi}{10\eta}} = d 10^{\frac{\Psi}{10\eta}}. \tag{3}$$

It might be worth remarking that the estimated distance $\hat{d}$ is biased. Though it is possible to correct this bias, for space constraints we do not provide any further detail on this respect. Instead, we report the relation between Ψ and the ranging error $\varepsilon_d = \hat{d} - d$, which is proportional to the distance itself d whose cumulative distribution function (cdf) turns out to be given by

$$F_{\varepsilon_d}(\alpha) = F_\Psi\left(\tilde{\psi}\right) = \begin{cases} 1 - \exp\left(-e^{(\tilde{\psi}-\mu_\psi)/\sigma_\psi}\right), & \text{if } \alpha > -d \\ 0, & \text{if } \alpha \leq -d \end{cases} \tag{4}$$

where

$$\tilde{\psi} = 10\eta \log_{10}\left(1 + \frac{\alpha}{d}\right) .$$

3 Multi-channel RSSI Sampling

As known, the impact of multipath on the received signal depends on the delay spread T_{rms} and the signal bandwidth B. If $T_{rms} \ll B^{-1}$ we can describe the radio propagation with a narrowband fading model, so that the received signal can be expressed as

$$r(t) = \Re\left\{ u(t) e^{j2\pi f_m t} \left(\sum_n a_n(t) e^{-j\phi_n(t)} \right) \right\} \tag{5}$$

where $u(t)$ is the complex envelope of the transmitted signal, $a_n(t)$ and $\phi_n(t) = 2\pi f_m \tau_n$ are the amplitude and the phase associated with the n–th multipath component, respectively, and f_m is the carrier frequency. We observe that the phase difference between the Line of Sight (LOS) path and a reflected path is given by

$$\Delta\phi_m = 2\pi f_m \frac{\delta}{c} \tag{6}$$

where δ is the difference between the length of the two paths and c is the propagation speed of the electromagnetic wave.

Now, the IEEE 802.15.4 standard entails a transmission pulse with bandwidth of 3 MHz which can be modulated over 16 different channels, with carrier frequencies equal to[1]

$$f_m = 2405 + 5(m - 11)\ [\text{MHz}]\,, \quad m = 11, \ldots, 26\,.$$

Furthermore, typical indoor values of T_{rms}, which can be found in [5], are generally less than 100 ns, so that we can safely assume that IEEE 802.15.4 signals are affected by narrowband fading.

Nonetheless, we notice that the phase difference (6) between the direct and reflected signal components may vary significantly for sufficiently different values of m. For instance, if we consider a reflect path $\delta = 3$ m longer than the direct path, the phase difference between the two signal components that we observe in channel $m = 11$, i.e., $\Delta\phi_{11}$ differs from $\Delta\phi_{21}$ of approximately π. This suggests that the stochastic component that affects the RSSI measures may be averaged out by taking the mean value of samples collected at different frequency channels.

To sustain this claim, we designed an extremely simple communication protocol that enables the collection of RSSI samples between any pair of nodes on different channels. Basically, when a node wants to initiate the data exchange it transmits a *request* packet over the default channel (26 in our case). Such a packet carries a field with the next channel to be used for that communication. If the node receives a *reply* then the next data fragment will be sent over the new scheduled frequency. Otherwise, it assumes that the communication link is lost and returns to the default channel.

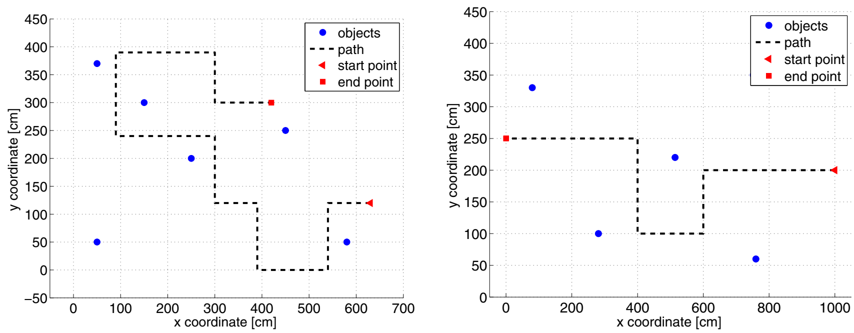
4 Experimental Campaign

This section describes the thorough experimental campaign that has been performed to collect the RSSI measurements we used to validate the channel model (1) with the Extreme Value statistical distribution for the multipath fading (2) and to sustain our claim regarding the reduction of the RSSI variations when averaging the samples collected in different channels.

For all the experiments we used Tmote Sky sensor nodes [4] mounting an isotropic antenna of known gain. These devices are equipped with the Chipcon wireless transceiver CC2420 [2] implementing the IEEE 802.15.4 standard

[1] We here respect the standard numeration of the IEEE 802.15.4 channels that conventionally goes from 11 to 26.

that specifies 16 channels with carrier frequencies $f_m = 2405 + 5(m - 11)$ MHz, $m = 11, ..., 26$. We considered three scenarios for the experimental campaign, that provide different environmental conditions. The collected data can be downloaded from the SIGNET group website [3].



(a) Setup #1. (b) Setup #2.

Fig. 1. Paths for experimental setups

Setup #1. The sensor nodes were deployed on boxes at 50 cm from the floor. Initially we collected RSSI samples from motes deployed on a grid (24 different positions), afterwards we deployed seven nodes at known positions into the room and with another mote we moved along a pre–planned path, collecting RSSI samples in 50 locations (see Fig. 1 for node positioning in indoor setups).

Setup #2. Five sensor nodes were deployed on cones at 30 cm from the floor in an aisle and another mote was used to collect RSSI samples every 50 cm along the path. In this environment there was no furniture so that the reflections of the transmitted signal are due mainly to the floor, walls and ceiling.

Setup #3. With the same devices used for setup #2 we deployed five of them uniformly into a 15 m x 8 m area, at 80 cm from the floor, outdoor. We collected RSSI samples by each pair of nodes and then we used another node to gather some more measurements over the area from the five static nodes.

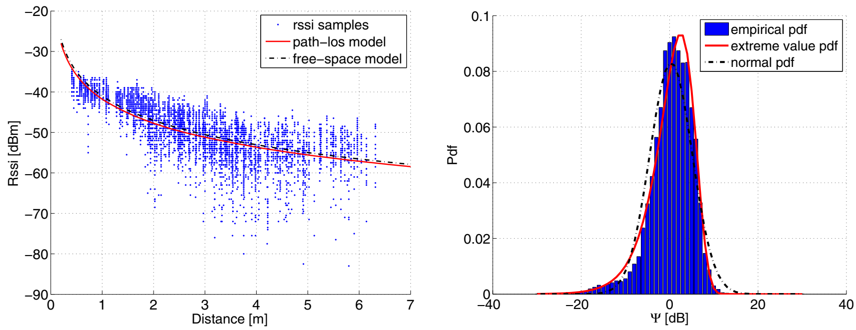
5 Results

Exploiting the collected RSSI measurements and the relative node distance information, we adopted a least mean square error criterion to obtain the channel parameters, i.e., K and η, and the standard deviation σ_ψ while we set $d_0 = 10$ cm.

With reference to setup #1 we conducted a measurement campaign to validate the channel model (1) and to evaluate the effect of multipath fading. Our experiments pointed out that it is not always necessary to estimate K and η. In fact, if the LOS condition is verified, their values are very close to those of the free–space case ($K \simeq -20$ dB and $\eta = 2$). Moreover, performing the estimation over a single channel gives us quite the same results, regardless of the particular carrier frequency, as shown in Table 1.

Table 1. Parameter estimation performed on single channels

	$ch11$	$ch12$	$ch13$	$ch14$	$ch15$	$ch16$	...	$ch21$	$ch22$	$ch23$	$ch24$	$ch25$	$ch26$
K dB	−21.7	−21.6	−21.7	−21.7	−22	−21.8	...	−21.3	−21.4	−22.1	−22	−22	−21.9
η	2.03	2.03	2	1.98	1.93	1.93	...	1.92	2.02	2.01	1.96	2	1.98
σ_ψ dB	4.8	4.4	4.5	4.4	4.3	4.5	...	4.2	4	4.1	4.3	4.4	4.2

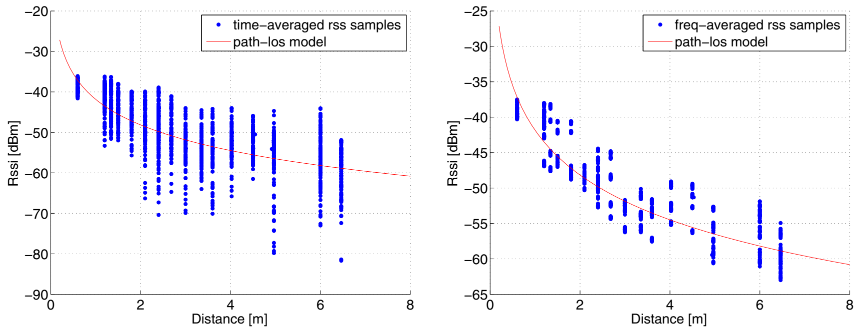


(a) Parametric model (b) pdf of Ψ

Fig. 2. Channel models of Setup #2

Fig. 2 validates the statistical channel model of Section 2: part (a) shows the collected RSSI samples (in blue), the model in (1) with parameters estimated from the samples (solid red line) and with the free–space parameters (dash–dotted black line). In addition, part (b) verifies that Ψ has an Extreme Value distribution, hence the received power (expressed in mW) is Weibull distributed. We obtained similar results for the outdoor scenario (setup #3), though in this case we observed that the multipath fading has less impact ($\sigma_\psi = 3.5$ dB).

To evaluate the gain achieved with multichannel transmission, we collected RSSI samples from several couples of nodes, changing carrier frequency every 100 ms and sweeping all the available channels. This routine was repeated 10 times, maintaining the same experimental setup. We observed, for a particular channel and for the same link, that the RSSI samples collected at different times are quite similar, with a standard deviation less than 2 dB. Conversely, the RSSI samples collected by a pair of nodes over the 16 different channels show a high variability, with standard deviation often greater than 4 dB. Thus, as confirmed by the comparison between Fig. 3(a) and Fig. 3(b), the standard deviation of the RSSI mean reduces when samples are collected over different frequency channels in a short time period, rather than on a single channel but over a longer time interval. The experimental results, in fact, returned $K = -19.8$ dB and $\eta = 2.1$ in the two cases, whereas σ_ψ varied from 2.8 dB (frequency–average) to 4.85 (time–average), with a gain of approximately 2 dB. Instead, in outdoor environment we revealed about 1 dB of improvement. Furthermore, we observed that the same gain can be obtained by considering just four samples taken at maximum distance frequencies.



(a) Time–averaged (b) Frequency–averaged

Fig. 3. Time– and Frequency–averaged RSSI samples

6 Conclusions

In this paper, we studied the properties of the radio signal propagation in WSNs using the IEEE 802.15.4 standard. In particular, we showed that a Weibull distribution accurately fits the signal fluctuations due to multipath fading for both indoor and outdoor scenarios. We designed and developed a simple multichannel communication protocol in order to validate our analytical framework with a thorough experimental campaign. To such extent, we collected RSSI samples in different network setups, that represent typical real wireless sensor network deployments. Our results show that significant performance improvements can be obtained averaging RSSI samples over frequency.

As a final consideration, not only the channel randomness, but also physical factors such as the antennas anisotropy, the actual device sensitivity, the channel asymmetry and topology aspects impact the RSSI reliability. Thus, the network design and the device characteristics must be taken into account for proper RSSI–based service realization.

Acknowledgments

This work has been supported in part by the FP7 EU projects “SENSEI” G.A. no. 215923, http://www.ict-sensei.org, “SWAP” G.A. no. 251557, and “IoT-A” G.A. no. 257521, and by the CaRiPaRo Foundation, Italy, within the WISE-WAI project, http://cariparo.dei.unipd.it

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