Link Quality Estimation for Future Cooperating Objects

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Abstract. In order to cooperate, smart objects need to communicate using wireless communication. Wireless communication, however, is inherently unreliable. Towards this end, the sensor networking community has developed a number of metrics for link quality estimation. Most of these metrics, however, are designed for static sensor networks whereas cooperating objects in many cases are mobile. In this position paper, we advocate a clean slate approach and develop a number of link quality metrics using a software defined radio. We show that our metrics are accurate and we believe that they are suitable for future radios for cooperating objects.

1 Introduction

Link quality estimation is often an indispensable component of a cooperating object's (CO) communication protocol stack, because it provides crucial information to trigger other operations such as topology changes and route updates. To support these operations, link quality estimation must be accurate in prediction of probable packet loss and agile to reflect changes in the environment. To estimate the quality of links in terms of the future packet reception rate (PRR) one can send a large amount of control packets. This approach, however, takes time and consumes energy. Therefore, researchers have also tried to exploit the hardware-based link quality metrics RSSI (Received Signal Strength Indicator), LQI (Link Quality Indicator) and SNR (Signal to Noise Ratio) [1]. These metrics, however, have inadequate accuracy under different channel conditions [2, 3].

Future low power radios used by CO will likely incorporate more digital signal processing capability as a result of lowered costs, which might be used for implementing new link quality estimation metrics. Towards this end, we implement three link quality estimation metrics for the IEEE 802.15.4 PHY standard [4] on a Software Defined Radio (SDR). The three metrics are Chip Error Rate (CER), Error Vector Magnitude (EVM) and Spectrum Factor (SF). SF is a new metric that we develop in this paper. It is used to show signal distortion in the frequency domain. We implement the metrics and evaluate them under four characteristic channel conditions. Our results show that the metrics can accurately estimate the PRR using only a single control packet. The high agility of our metrics is particularly suitable for CO that are inherently mobile.

Our main contributions are the following:

- We develop three agile and accurate link quality estimation metrics for CO
- we evaluate the performance of individual and combined metric
- our results can be used by radio manufacturers to improve the metrics in their hardware

2 Design and Implementation

In this section we describe the design and implementation of the three metrics CER, EVM and SF on GNU Radio, an SDR library. We use the UCLA ZigBee library [5], a GNU Radio extension, to carry out IEEE 802.15.4 PHY functions.

To improve robustness against interference, the IEEE 802.15.4 2.4GHz physical layer uses a direct sequence spread spectrum (DSSS) technique to expand the data bits from a PHY packet to a sequence of binary numbers, aka chips, before transmission [4]. The chip sequence contains redundant information about the original packet that a receiver can use to recover partial chip errors. We mark the error chips by performing a chip-to-chip comparison between the received sequence and the most likely original sequence. We then derive the received packet's chip error rate by taking the ratio between the number of error chips and the total number of chips in the packet.

$$CER = \frac{N_e}{N} \times 100\%$$

Every two chips are converted into a symbol in the complex signal domain before transmission. A symbol is represented by a two-dimensional spatial vector, Whose length and direction represent the amplitude and phase of the symbol respectively. The receiver always observes a certain degree of signal distortion, visible as the difference between the received symbol vector and the ideal vector. To quantify the degree of distortion, an error vector can be drawn between the two vectors, and its length is termed Error Vector Magnitude. Due to our SDR demodulator's omission of the received symbol's amplitude information, we define the symbol distortion as the phase error between the received and ideal symbol vectors instead, while keeping the common term EVM:

$$EVM = \sqrt{2 - 2cos\phi} \times 100\%$$

A packet's overall EVM is obtained by taking the average of all received symbols' EVMs.

Since a signal spans over a certain frequency band, and various types of noise and interference are often frequency specific, we believe it would be interesting to show the signal distortion in the frequency domain as well, by means of spectrum analysis. As we conceive of a measurement of the frequency-domain signal distortion, we take two factors into consideration: meaningful signal spectrum components; and computation complexity. We come up with a signal quality metric for 5 MHz-wide IEEE 802.15.4 signals, taking the ratio between the energy of the first order component and that of the sum of the two second order

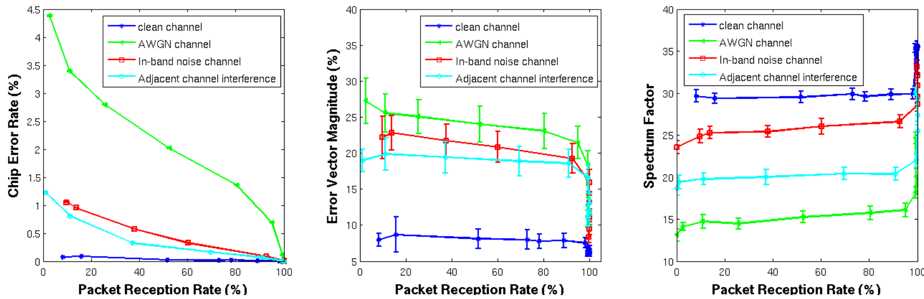
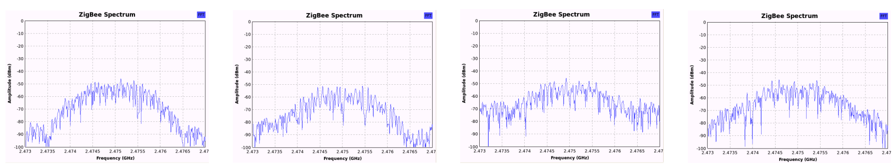


Fig. 1. Comparison of metrics with different channel conditions



(a) Clean channel (b) Adjacent channel interference (c) AWGN channel (d) In-band noise

Fig. 2. Comparison of spectrums with different channel conditions

components, and call this the "Spectrum Factor" (SF). In the equation below, we denote the received signal in the frequency domain as $X(f)$ and its central frequency as f_c. Because the computation consists of only bandpass filtering and integration, SF should be simple enough to be implemented by low cost digital hardware as well. We sample 2 bytes from a packet to determine its SF.

$$SF = \frac{\int_{f_c-1.5M}^{f_c+1.5M} |X(f)|^2}{\int_{f_c+1.5M}^{f_c+2M} |X(f)|^2 + \int_{f_c-2M}^{f_c-1.5M} |X(f)|^2}$$

3 Evaluation

We test the three metrics under four different channel conditions: clean channel, adjacent channel interference, additive white Gaussion noise (AWGN), and in-band noise. The last three characterize different sources of noise and interference that result in distortion and possible packet loss. Fig. 2 shows an a clean channel signal and three different distortions to the original signal, observed by a spectrum analysis function implemented at the receiver.

We show the three metrics' relation with PRR to reveal their accuracy under the four channel conditions in Fig. 1. The standard deviations are plotted as error bars on each curve.

CER has the best overall stability among the three metrics under all channel conditions. The ranges of CER depends on channel conditions. In the AWGN channel, CER increases to 4.5% when the PRR decreases to 0%. But in the clean channel, CER is always below 0.1%.

EVM has very good sensitivity for changes in PRR, when PRR is higher than 95%. EVM increases from 6% up to 21% as PRR degrades from 100% to 95%. This can be used to track a fading link between two mobile nodes. The variation of EVM in this range is low.

SF does not rely on successful synchronization or demodulation as EVM and CER, hence can be performed even on unsuccessfully demodulated packets. This enables SF estimation faster than CER and EVM when the link is very weak. SF has a fairly small standard deviation and reasonable sensitivity for a PRR lower than 10% under the three noisy channel conditions.

An important observation from the results is that the three metrics behave differently under different channels conditions. In order to improve accuracy, we need to characterize a link's channel condition. A clean signal has a large first order component and two balanced second order components; Noise from an adjacent channel increases one of the second order components, as shown in Fig. 2(b); AWGN moves the whole spectrum up, as shown in Fig. 2(c). The presence of in-band interference, as shown in Fig. 2(d), is obscure, since spectrums of the signal and the interference overlap evenly across the whole band. A heuristic algorithm can be developed to characterize the current channel condition by matching the above spectral patterns to one of the four channel conditions.

Therefore, we propose a link quality estimation approach that apply the three metrics together. The channel condition is first characterized. Then CER is used to approximately estimate the PRR. EVM can be applied to obtain a highly accurate PRR estimation for a PRR range between 95% and 100%. On the other hand, SF can be used to estimate a very weak link.

4 Conclusions

We have presented three metrics that require only one received packet to estimate link quality. This makes the metrics attractive for future mobile CO. Moreover, combining the three metrics integrates their advantages and provides better accuracy.

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