

An adaptive channel quality metric for ultra-narrowband systems

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Abstract—In this paper, we propose an adaptive channel quality metric that is suitable for uplink channel estimation in ultra-narrowband networks. The proposed metric relies on channel measurements rather than on packet information, therefore it doesn't need a large number of packets to initialize, and is simple enough that can be computed per channel for a large number of channels. Our results show that the proposed metric should be able to identify channels with the least amount of interference for a wide range of expected received packet powers.

Keywords—channel quality, narrowband transmissions, internet of things, cyber physical systems, maximum likelihood estimation, spectrum sensing, RSSI, empirical data, measurements, method

I. INTRODUCTION

The Internet of Things relies on battery-operated, low-complexity and low-cost devices. These devices also tend to produce and transfer data, rather than receive and process. As a result, the protocols they use for communication have to be optimized for uplink data transmission. Low Power Wide-Area Networks (LP-WAN) [1] communication technologies are emerging as the de-facto IoT enablers. These technologies contrast existing widely deployed wireless technologies, such as LTE and IEEE 802.11 WLAN, that have been optimized for low-latency, high-throughput links required by multimedia applications on laptop computers and smartphones.

Recently, a number of LP-WAN technologies and standards have emerged [1]. A sub-class of these technologies employ ultra-narrowband (UNB) transmissions, such as SIGFOX [2] and Weightless [3]. These protocols use a physical layer that employs very low bit-rate transmissions (on the order of 100 to 1000 bits/s) using Binary Phase Shift Keying (BPSK) or Gaussian Frequency Shift Keying (GFSK) modulations with bandwidths on the order of 100 Hz to 1 kHz. This enables them to reach high spectral efficiency and low preamble overhead with short payloads [4].

However, if UNB networks reach predicted deployment numbers and densities, they will have to ensure QoS in the presence of *inter-technology interference* that comes from other technologies sharing the same frequency bands and *intra-technology interference* resulting from increased device density in a network [5]. Having an accurate estimate of a quality of the channel can help employing various interference avoidance techniques. While there are a number of channel quality estimators proposed in the literature [6]–[9], they focus

on downlink link estimation techniques using a relatively small number of channels. Many of the channel quality estimators use pre-computed models and are more difficult to adapt over time.

In this work, we are specifically interested in a channel quality estimator that can provide a reliable prediction for packet loss based on a history of RSSI measurements from the spectrum sensor. We focus on uplink channel estimation for ultra-narrowband system where the number of channels is typically in the thousands. We extend the work on existing estimators with a new maximum likelihood estimator and we compare this estimator to the state of the art. We also propose a method to compute the estimator using empirical PRR(SINR) data in devices that do not have the capability to reliably estimate SINR directly. The proposed channel quality metric can be used by a basestation to choose channels for whitelisting, thus avoiding interference. The architecture of such a closed loop optimization system has been described in our previous work [5]. An example instantiation of the closed loop architecture and some of the software we developed and data we collected for this line of research are available on our Github ¹².

An alternative approach to the one proposed in this paper would be to base our channel quality metric on the past packet loss for individual channels. However, this approach has a significant drawback: a large number of packets must be sent before a reliable statistic per channel can be generated. This problem is further emphasized by the large number of channels in a typical ultra-narrowband system. It also follows that using this approach a large number of packets must be lost before a channel is recognized as unfavourable. This packet loss might be unacceptable for the required quality of service in the network.

This paper is organized as follows. Section II provides an overview of the most relevant channel quality metrics, Section III presents the proposed maximum likelihood estimator channel quality metric while Section IV describes and validates a mask based empirical computation of PRR as a function of SINR. Section V reports the results of the evaluation of the proposed metric while Section VI concludes the paper.

¹Toolbox <https://github.com/sensorlab/sigfox-toolbox>

²Packet datasets <https://github.com/sensorlab/sigfox-packet-datasets>

II. OVERVIEW OF CHANNEL QUALITY METRICS

A. Mean channel availability

One simple channel quality metric that was considered for our purpose is the mean channel availability (MCA). It is defined as a percentage of time where interference power in a channel is below a threshold R_{thr} . Say our spectrum sensor samples the channel power P_i at times t_i , $i \in [1, 2 \dots]$, then this metric can be defined as:

$$MCA = \frac{1}{N} \sum_{i=i_0}^{i_0+N} s_i \quad (1)$$

where

$$s_i = \{0 \text{ if } P_i < R_{thr}, 1 \text{ otherwise}\} \quad (2)$$

and

$$R_{thr} = R_{rx} - SINR_{min} \quad (3)$$

where R_{rx} is the power of the received signal from the devices at the base station and $SINR_{min}$ is the minimum signal-to-noise-and-interference ratio at which the base station is able to receive the signal.

This metric is problematic, since it assumes a sharp threshold in SINR upon reception. In other words, it assumes that 100% of packets will be lost if interference is above a certain threshold and 0% packet loss otherwise. In reality, the packet loss more or less slowly transitions between these two extremes as SINR deteriorates.

B. Mean signal power

A metric that attempts to address the shortcomings of the mean channel availability is the mean signal power (MSP) over a time window:

$$MSP = \frac{1}{N} \sum_{i=i_0}^{i_0+N} P_i \quad (4)$$

A problem with the mean signal power metric is that it does not take into account the time distribution of interference. Consider a channel where a single strong interferer very occasionally transmits and a channel where a weak interferer transmits continuously. The MSP metric will consider both of these channels identical, however the first channel will have very little packet loss since the probability that a packet in the network will collide with the infrequent interferer will be very low. On the other hand, the second channel will continuously lose packets due to constant interference.

C. Time aware channel quality

A metric that attempts to account for time distribution of interference is the $CQ(\tau)$ metric [8], referred to as time-aware channel quality metric in this paper:

$$CQ(\tau) = \frac{1}{n-1} \sum_{j|(j-1)P > \tau} j^{1+\beta} m_j \quad (5)$$

Here n is the number of samples in a time window where the metric is calculated. m_j is the number of opportunities where the channel is vacant for j consecutive samples. The metric considers the channel vacant when the measured power in the channel is below threshold R_{thr} (equation 3). P is the channel power sampling period. τ is the time duration of the packet being transmitted.

$j \cdot m_j$ is the total number of channel power samples that appear in vacancies of length j . The metric sums up all such opportunities where their length $(j-1)P$ is longer than the duration of the packet being transmitted τ . It then divides the number of samples with the total number of samples n in the time window being considered. The authors of [8] also chose to include another parameter, β , that determines the bias of the metric towards the channels that have longer transmit opportunities. It is not clear how to determine the value for β for best packet reception ratio.

III. A NEW, ADAPTIVE, MLE CHANNEL QUALITY METRIC

We propose a maximum likelihood estimate (MLE) metric, referred to as \overline{PRR} , that estimates the probability of successful transmission of a packet with length τ , assuming any instance of interference more powerful than R_{thr} results in a lost packet. Hence, to compute the MLE channel quality, the total number of observed transmit opportunities n_{total} and the number of observed transmit opportunities that did not encounter interference stronger than R_{thr} , n_{clear} , have to be computed as follows:

$$MLE = \frac{n_{clear}}{n_{total}} \quad (6)$$

The total number of observed transmit opportunities depends on the length of the observed time window n and the length of the transmitted packet in samples τ/P :

$$n_{total} = n - \tau/P \quad (7)$$

The number of observed transmit opportunities with no interference can be written as follows (using same variables as in Equation 5):

$$n_{clear} = \sum_{j|(j-1)P > \tau} (j - \tau/P) m_j \quad (8)$$

Since calculating the MLE requires the same data as calculating the $CQ(\tau)$ metric and does not need the β parameter, we can refer to it as a simplified channel quality metric:

$$CQ^*(\tau) = \frac{1}{n - \tau/P} \sum_{j|(j-1)P > \tau} (j - \tau/P) m_j \quad (9)$$

However, the simplified channel quality metric CQ^* does not take into account that probability of successful frame reception smoothly varies with SINR. Therefore, the proposed MLE estimator considers the smooth variation as follows.

Given a recorded history of interference power measurements in a channel, we can estimate the mean interference power over the duration of a hypothetical packet transmission starting at sample i_0 (time t_{i_0}):

$$\overline{P_{IN}}(i_0) = \frac{1}{\tau/P} \sum_{i=i_0}^{i_0+\tau/P} P_i \quad (10)$$

where P_i is measured interference power in the channel at instance t_i . Then hypothetical SINR during reception can be approximated by:

$$\text{SINR}(i_0) = \frac{R_{rx}}{\overline{P_{IN}}(i_0)} \quad (11)$$

Assuming we know the packet reception ratio (PRR) as a function of SINR, we can calculate the predicted mean PRR for the channel by averaging calculated PRRs for all possible packet transmission times:

$$\overline{\text{PRR}} = \frac{1}{n - \tau/P} \sum_{i=0}^{n-\tau/P} \text{PRR}(\text{SINR}(i_0)) \quad (12)$$

IV. A METHOD FOR EMPIRICALLY ESTIMATING PRR(SINR)

The proposed MLE channel estimator from eq. 12 requires the packet reception ratio as a function of the signal-to-noise-and-interference ratio. This is a characteristic of the receiver that depends on the receiver design, modulation, etc. Analytical calculations exist for various modulations and Gaussian noise. For example, for BPSK, the bit error rate is equal to [10]:

$$P_b = \frac{1}{2} \text{erfc}\left(\sqrt{\frac{E_b}{N_0}}\right) \quad (13)$$

However, unlike in theoretical studies, real receivers 1) only approximate optimal decoding and 2) noise and interference are not Gaussian. Hence we propose a possible method to compute the PRR(SINR) of a real ultra-narrowband receiver using empirical data retrieved from this receiver. The method uses only channel power measurements and is suitable for devices that do not have the capability to reliably estimate SINR directly.

A. Data collection

To collect empirical data, the following experimental set-up was used. The transmitter, a USRP N200 device, was located indoor and sent 1000 packets to an outdoor ultra-narrowband base station. All packets were sent on a single channel in the 868 MHz band for easier post processing of data. To vary the signal-to-noise ratio of the packets, the transmitter varied the transmit power by randomly changing the baseband gain from -50 to -20 dB. This range was chosen empirically to cover the entire range of PRR, from 0 to 100%.

On the base station side the power spectral density on the base station antenna (in the form of RSSI samples for all uplink channels) and the received packets were recorded simultaneously. Based on the sequence numbers of the packets the received packets were matched with transmitted packets. The transmitted packets that were not received successfully were marked as lost. Data about received packets was also correlated with spectrum recording, adjusting for time and frequency offsets.

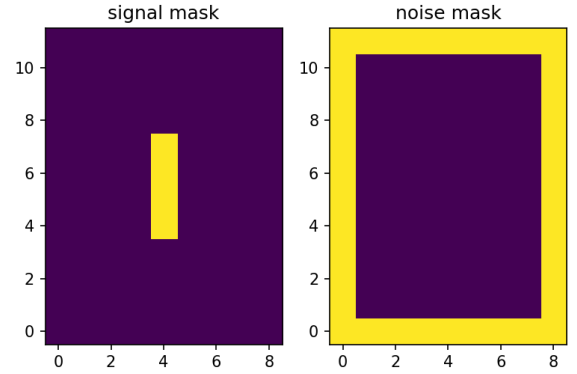


Fig. 1. Masks used to estimate signal and interference plus noise power from RSSI recordings. Frequency is on the horizontal axis and time is on the vertical axis. Yellow color shows 1, purple shows 0.

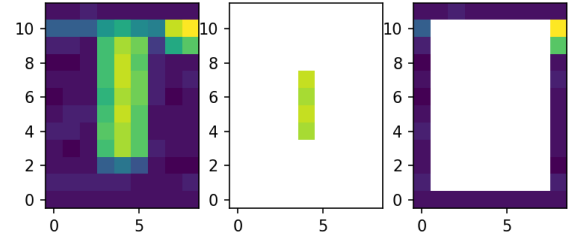


Fig. 2. Effect of applying masks to spectrum recording of a single transmission. Left: unmasked data. Center: masked data for signal. Right: masked data for noise and interference.

B. SINR computation using masks

Our base station did not have the capability to reliably estimate SINR directly so in the proposed implementation we had to find a practical solution. Hence to calculate SINR at the receive side for each transmitted packet we used the recorded spectrum data. For each packet we had to estimate the received signal strength and noise and interference power. We did this by summing RSSI samples from the recorded spectrum data using two masks: one that covered only the signal transmission (Figure 1, left) and one that covered the immediate surroundings of the transmission (Figure 1, right). We were able to do this since the transmitted packets had known time duration and frequency bandwidth. For base stations with SINR estimation capabilities or situation with unknown packet durations, a different solution should be adopted for SINR computation. Figure 2 shows these masks applied to real data for a single packet.

We assumed that power P_1 estimated using the first mask included signal power as well as interference and noise power. Similarly, power P_2 estimated using the second mask included only interference and noise power. We also assumed that interference and noise power was constant during the time-frequency window:

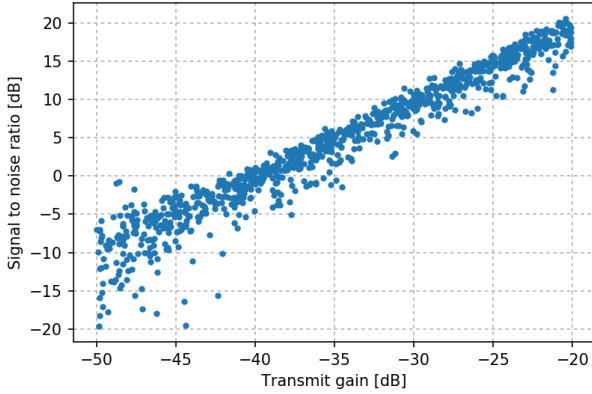


Fig. 3. Estimated SINR versus transmit gain.

$$P_1 = S + I + N \quad (14)$$

$$P_2 = I + N \quad (15)$$

From these two samples we could estimate SINR for each packet:

$$SINR = \frac{P_1 - P_2}{P_2} \quad (16)$$

C. Validation

To validate the proposed computation of SINR using masks, the computed SINR was plotted against the transmit gain as shown in Figure 3. The empirically computed SINR shows linear dependence on the transmit gain, which validates our method using masks works as expected.

The empirically computed SINR vs. PRR was also plotted to validate the S shaped function that is known to link the two variables [11]. Figure 4 plots the result of this estimate and validates the S shaped function.

V. RESULTS

We applied the presented metrics to passive spectrum measurements of the activity in the 868 MHz European SRD band in Ljubljana between 29 May and 14 June 2017. The MCA availability is depicted in Figure 5(a). The simplified channel availability metric from Equation 9 is depicted in Figure 5(b). Figures 5(c) and 5(d) show the proposed channel metric \overline{PRR} computed using empirical data and theoretical formula for $PRR(SINR)$ respectively. In all the figures, the frequency (channel) is on the horizontal axis, the channel quality metric is on the vertical axis. All metrics have been calculated for a range of expected received packet powers levels R_{rx} (or, equivalently, thresholds R_{thr} from Equation 3). The received power level is shown on the color scale. Dashed lines on the plots highlight specific values of R_{rx} or R_{thr} . For each subfigure, two ranges of the vertical axis are shown: full range 0 - 1 (bottom) and a zoomed-in view close to 1 (top).

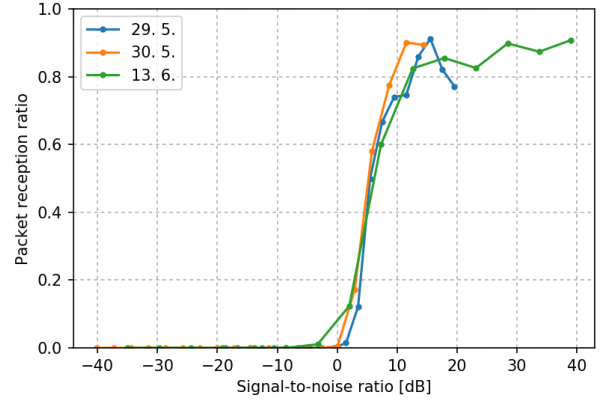


Fig. 4. Estimated PRR versus SINR for 3 measurement campaigns performed on different dates.

We can see that all presented metrics identify certain parts of the spectrum that are more favourable (e.g. between 868.560 MHz and 868.620 MHz) and less favourable (e.g. around 868.525 MHz and 868.665 MHz). The estimated channel quality also differs significantly with the packet received power. This is expected: with a low enough received power, the base station will not be able to decode the packet, regardless of any interference. The differences between channels are largest when the received power is similar to interference power.

From our results, MCA shows the least difference between channels. On the other hand, the $CQ^*(\tau)$ metric shows significant differences between occupied and vacant channels. As expected, the \overline{PRR} metric shows more gradual change in metrics as R_{rx} decreases, due to the smooth S-shaped curve of the $PRR(SINR)$ characteristic, in contrast to the sharp threshold assumed by the other two metrics.

VI. CONCLUSION

In this paper we have presented some existing channel quality metrics that we found suitable for application to ultra-narrowband networks. We have also proposed a new channel quality metric based on maximum likelihood estimation of packet reception rate. Since our metric requires knowing how PRR varies with SINR, we have shown how this characteristic can be estimated using only channel power measurements. This makes it possible to apply our method when using equipment that does not provide direct SINR measures for received packets. The results of our evaluation suggest that the proposed metric should be able to identify channels with the least amount of interference for a wide range of expected received packet powers. As future work, the evaluation of the benefits of the proposed metric in a real network should be performed. This involves a more comprehensive experiment using real packet transmissions in an operating network. Channel selections based on different channel metrics could be compared based on actual PRR and would provide a good insight into its applicability.

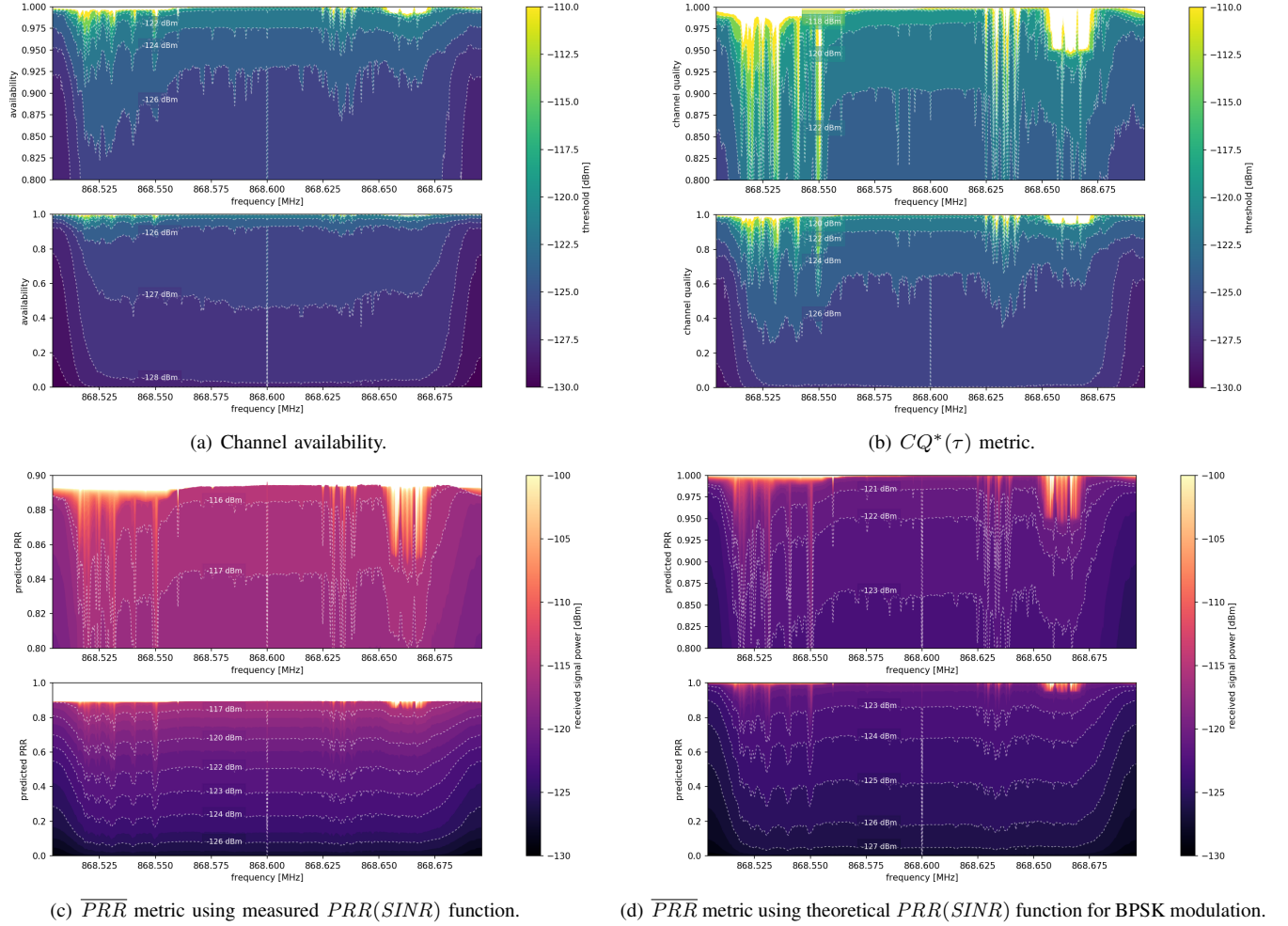


Fig. 5. Channel quality estimators.

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