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Evaluating the Impact of Signal to Noise Ratio on IEEE 802.15.4 PHY-Level Packet Loss Rate

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Abstract

In this paper, we evaluate the impact of signal to noise ratio (SNR) on the PHY-level packet loss rates on IEEE 802.15.4 links under the additive white gaussian noise and Rayleigh fading models. We show that IEEE 802.15.4 PHY-level packet loss rate has a step-like response to the SNR deterioration. In other words, the packet loss rate is largely unaffected by SNR deterioration as long as SNR is more than a threshold. However, even a small deterioration in SNR beyond this threshold causes the packet loss rate to approach 1. This result implies that SNR may not serve as a fine-granularity metric to indicate the reliability of an IEEE 802.15.4 link.

1. Introduction

In recent years, we have witnessed a strong push towards the adaption of wireless communication technology in various commercial monitoring and non-critical control applications. The elimination of wires not only promises significant cost savings but also an unprecedented increase in the scale of these applications. One of the main driving factors in this regard has been the standardization of IEEE 802.15.4 protocol [1]. IEEE 802.15.4 defines low power and low data rate PHY and MAC protocols suitable for use in wireless sensor networks. The PHY layer protocol defines operation in several frequency bands, the most prominent being the 2450 MHz *industrial, scientific and medical* (ISM) band where the protocol uses *orthogonal quadrature phase shift keying* (O-QPSK) modulation [2] to support a data rate of 250 Kbps. The MAC layer protocol is based on *carrier sense multiple access with collision avoidance* (CSMA/CA). IEEE 802.15.4 has rapidly emerged as the MAC/PHY protocol of choice for various monitoring/control applications. The *IPv6 over Low Power WPAN* (6lowpan) working group [3] at *Internet Engineering Task Force* (IETF) is currently engaged in enabling IPv6 operations over IEEE 802.15.4 networks and the *Routing Over Low-power and Lossy Networks* (ROLL) working group [4] is developing a highly scalable routing protocol, RPL [5], for low power and lossy networks including IEEE 802.15.4 networks. Popular Zigbee suite also uses IEEE 802.15.4 as the MAC/PHY protocol [6].

Operation of a routing protocol in an IEEE 802.15.4 network requires the assignment of routing costs to the links between nodes and/or to the nodes themselves. A wide range of metrics can be used to determine a link's routing cost. Some of the popular metrics include link reliability, link latency and the energy cost of packet transmission/reception on the link. Link reliability is an important metric that is often used exclusively or in conjunction with other metrics to determine the routing cost of the links. Link reliability may be measured as the packet success/error rate on the link or as the expected number of transmissions (ETX) to successfully send a packet to the other end of the link [7]. Often, the link reliability is measured in terms of the *received signal strength indicator* (RSSI), which is an indication of the radio energy in the communication channel during the transmission of a packet. Since this radio energy includes both the signal energy as well as the noise energy, RSSI may not be a good indicator of the signal energy alone or of the *signal to noise ratio* (SNR), which is defined as the ratio of the signal and noise energy levels in the communication channel. In spite of this shortcoming, RSSI continues to be a popular choice as an indication of SNR on the link, which in turn is used as a measure of link reliability.

The surprising popularity of RSSI as a measure of link reliability stems to a large extent from the belief that the SNR on the link is a good indication of its reliability. In this paper, we investigate this belief. Specifically, we investigate the impact of SNR deterioration on the PHY-level packet loss rate on

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an IEEE 802.15.4 link under *additive white gaussian noise* and *Rayleigh fading* models. We show that IEEE 802.15.4 PHY-level packet loss rate has a step-like response to the SNR deterioration. In other words, the PHY-level packet loss rate is largely unaffected by SNR deterioration as long as SNR is more than a threshold. However, even a small (less than 10 dB; some times as small as 3 dB) deterioration in SNR beyond this threshold causes the PHY-level packet loss rate to approach 1. This result implies that SNR or RSSI should not be used as a fine-granularity metric to indicate the reliability of an IEEE 802.15.4 link for use in the operation of routing protocols such as Zigbee [6] and RPL [5].

The rest of the paper is organized as follows. Section 2 describes the packet transmission and reception procedure in popular 2450 MHz operation of IEEE 802.15.4 PHY layer. Section 3 calculates the probability that an IEEE 802.15.4 PHY node fails to correct an n-chip error in the received 32-chip sequence sent for a 4-bit *symbol*. Section 4 builds on this analysis to determine the probability of receiving a packet in error on an IEEE 802.15.4 link operating in 2450 MHz range given the signal to noise ratio (SNR) under *additive white gaussian noise* and *Rayleigh fading* models. This section also analyzes the impact of SNR deterioration on the IEEE 802.15.4 PHY-level packet loss rate. Section 5 concludes the paper.

2. Packet Transmission and Reception in IEEE 802.15.4 PHY Operation in 2450 MHz Range

IEEE 802.15.4 PHY layer is responsible for transmission and reception of data to/from the radio channel and can operate in many different frequency ranges. Popular 2450 MHz operation of IEEE 802.15.4 PHY layer offers a maximum data rate of 250 Kbps and is based on *direct sequence spread specturm* (DSSS) technology employing *offset quadrature phase-shift keying* (O-QPSK) modulation. There are 16 communication channels available in 2450 MHz range and each channel is 5 MHz wide.

Each packet in 2450 MHz PHY operation begins with a 5 byte (or 10 *symbols*[1]) long *synchronization header* and a 1 byte (or 2 symbols) long PHY header. These fields are followed by a variable length (up to 127 bytes) PHY payload. The actual transmission takes place 1 *symbol* (or 4 bits) at a time. A 4-bit long symbol is translated to one of 16 *nearly orthogonal* 32-chip long *pseudo-random noise* (PN) sequences shown in Table 1. The PN sequences for successive data symbols are concatenated and the resulting chip stream is modulated onto the carrier using O-QPSK with even-indexed chips being modulated onto the *in-phase* carrier and odd-indexed chips modulated onto the *quadrature-phase* carrier.

The packet reception at the PHY layer works as follows. The received signal is demodulated to retrieve the chip stream and the individual 32-chip sequences. A received sequence is compared against 16 valid PN sequences and the one showing the smallest *hamming* distance from the received sequence is chosen as the transmitted sequence and is translated back to the corresponding symbol. Here, the hamming distance refers to the number of chip positions the two chip sequences differ in [2]. Thus, a transmitted symbol will be correctly identified as long as the hamming distance between the received sequence and the transmiited sequence is smaller than the hamming distance between the received sequence and any other valid sequence. Any error in identifying the transmitted symbols is likely to be identified when the packet checksum is calculated and compared with the checksum carried in the packet's header.

3. The Probability of Symbol Error in IEEE 802.15.4 PHY Operation

As mentioned in the previous section, the receiver correctly identifies the transmitted symbol if the hamming distance between the received and the transmitted sequence is smaller than the hamming distance between the received sequence and any other valid sequence. In this section, we calculate the probability that the receiver fails to identify the transmitted symbol correctly, i.e., the hamming distance between the received sequence and the transmitted sequence is equal to or higher than that between the received sequence and another valid sequence.

Table 2 shows the hamming distance between each pair of 32-chip PN sequences shown in Table 1. Table 2 shows that each valid chip sequence differs from other valid chip sequences in at least 12 positions and atmost 20 positions. A closer look reveals that each valid chip sequence has:

- a hamming distance of 12 from 2 other valid chip sequences;
- a hamming distance of 14 from 2 other valid chip sequences;
- a hamming distance of 16 from 3 other valid chip sequences;
- a hamming distance of 18 from 2 other valid chip sequences; and

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[1] Each symbol consists of 4 bits.

Chip Sequence Number	**Data Symbol b0 b1 b2 b3**	**Chip Sequence c0 c1 ... c30 c31**
1	0000	11011001110000110101001000101110
2	1000	11101101100111000011010100100010
3	0100	00101110110110011100001101010010
4	1100	00100010111011011001110000110101
5	0010	01010010001011101101100111000011
6	1010	00110101001000101110110110011100
7	0110	11000011010100100010111011011001
8	1110	10011100001101010010001011101101
9	0001	10001100100101100000011101111011
10	1001	10111000110010010110000001110111
11	0101	01111011100011001001011000000111
12	1101	01110111101110001100100101100000
13	0011	00000111011110111000110010010110
14	1011	01100000011101111011100011001001
15	0111	10010110000001110111101110001100
16	1111	11001001011000000111011110111000

Table 1. 32-chip PN Sequences for 4-bit Symbols [1]

- a hamming distance of 20 from 6 other valid chip sequences.

Consider the following scenario:

- The hamming distance between the received 32-chip sequence R and the sent 32-chip sequence S is x;
- The hamming distance between the received sequence R and another valid 32-chip sequence A is y;
- The hamming distance between sequence S and sequence A is d;
- Sequences R and A differ in z of the d chips, where S and A are different, and in $y - z$ of the $32 - d$ chips, where S and A are same.

The last point mentioned above implies that sequences R and S differ in $d - z$ of the d chips, where S and A are different, and in $y - z$ of the $32 - d$ chips, where S and A are same. In other words, $x = d - z + y - z = d + y - 2 * z$. Thus, $x < y$ if $d < 2 * z$. Thus, the receiver will not mistake A as the sent sequence as long as $d < 2 * z$ or $z > d/2$.

Since the minimum hamming distance between any two valid chip sequences is 12, any 5 or fewer chip errors between the sent and the received sequences can always be corrected. This is because, in these cases, the sent sequence would still have smaller hamming distance from the received sequence than any other valid sequence. Similarly, it can be shown that 26 or more chip errors between the sent and the received sequence can never be corrected. This is because, in these cases, every other valid sequence will have a smaller or equal hamming distance from the received sequence than the sent sequence. For example, if the hamming distance between the sent (S) and received (R) sequence is 26 and that between the sent and another valid sequence (A) is 12, then the maximum hamming distance between R and A would be 26 (this happens when R and S differ in all 20 chips where S and A are same).

To determine the actual chip error tolerance of IEEE 802.15.4 PHY, we calculated whether a receiver would be able to correct a particular permutation of chip errors in a particular chip sequence, i.e., whether for this particular permuation of chip errors, the hamming distance between the received and the sent sequence would be smaller than the hamming distance between the received sequence and any other valid sequence. This calculation was performed for each possible permutation of chip errors of each possible cardinality for each valid sequence. This information was then used to calculate the probability that an n-chip error, where n ranges from 1 to 32, in the sent sequence would result in a symbol error. This calculation was based on the assumption that each possible permutation of an n-chip error is equally likely. The results are shown in Table 3. Note that all 14 or more chip errors in the received sequence are certain to result in a symbol error.

4. Signal to Noise Ratio Versus Packet Error Rate in 2450 MHz IEEE 802.15.4 PHY Operation

As discussed in Section 2, the chip sequences for successive data symbols are concatenated and the resulting chip stream is modulated onto the carrier using *offset quadrature phase shift keying* (O-QPSK). In this section, we combine the probability of a chip error for an O-QPSK modulated chip stream for a given signal to noise ratio (SNR) with the symbol error probability determined in the previous section to obtain the PHY-

Chip Sequence	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
1	0	16	18	20	20	20	18	16	16	12	14	20	20	20	14	12
2	16	0	16	18	20	20	20	18	12	16	12	14	20	20	20	14
3	18	16	0	16	18	20	20	20	14	12	16	12	14	20	20	20
4	20	18	16	0	16	18	20	20	20	14	12	16	12	14	20	20
5	20	20	18	16	0	16	18	20	20	20	12	12	16	12	14	20
6	20	20	20	18	16	0	16	18	20	20	20	14	12	16	12	14
7	18	20	20	20	18	16	0	16	14	20	20	20	14	12	16	12
8	16	18	20	20	20	18	16	0	12	14	20	20	20	14	12	16
9	16	12	14	20	20	20	14	12	0	16	18	20	20	20	18	16
10	12	16	12	14	20	20	20	14	16	0	16	18	20	20	20	18
11	14	12	16	12	14	20	20	20	18	16	0	16	18	20	20	20
12	20	14	12	16	12	14	20	20	20	18	16	0	16	18	20	20
13	20	20	14	12	16	12	14	20	20	20	18	16	0	16	18	20
14	20	20	20	14	12	16	12	14	20	20	20	18	16	0	16	18
15	14	20	20	20	14	12	16	12	18	20	20	20	18	16	0	16
16	12	14	20	20	20	14	12	16	16	18	20	20	20	18	16	0

Table 2. Hamming distance between each pair of 32-chip PN Sequences

The number of chip errors, n	The probability of symbol error, $P_{symerr}(n)$
5 and less	0
6	0.0020
7	0.0134
8	0.0523
9	0.1498
10	0.3479
11	0.6496
12	0.9156
13	0.9968
14 and more	1

Table 3. The probability of symbol error (rounded to 4 places of decimal) in IEEE 802.15.4 PHY for a given number of chip errors in the received sequence.

level packet error rate for 2450 MHz IEEE 802.15.4 operation.

The probability of bit error (or the *bit error rate*) for an O-QPSK modulated signal under *additive white gaussian noise* (AWGN) is given by [2]:

$$B = \frac{1}{2} erfc(\sqrt{\gamma}) \tag{1}$$

where *erfc* is the complementary error function, γ is the ratio of the signal energy to the noise energy.

AWGN does not take in account the impact of *fading*. The probability of bit error (or the bit error rate) for an O-QPSK modulated signal under *Rayleigh fading* model, which represents the scenario where there is no significant line of sight component between the transmitter and receiver, is given by [2]:

$$B = \frac{1}{2}\left(1 - \sqrt{\frac{\gamma}{1+\gamma}}\right) \tag{2}$$

where γ is the signal to noise ratio.

If B is the probability of receiving a chip in error and $P_{symerr}(n)$ is the probability of symbol error when n chips are received in error (Table 3), the probability S of interpreting a symbol incorrectly (or the *symbol error rate*) is given by:

$$S = \sum_{n=1}^{32} \binom{32}{n} B^n (1-B)^{32-n} \times P_{symerr}(n) \tag{3}$$

A packet is received in error if any of its symbols is received in error. Thus, if a packet is m bytes (or $2m$ symbols) long, the probability P of receiving a packet in error (or the *packet error rate*) is given by:

$$P = 1 - (1-S)^{2m} \tag{4}$$

Figures 1(a) and 1(b) show the deterioration in bit, symbol and packet error rates as the SNR deteriorates under AWGN and Rayleigh fading model respectively. The packet error rates are calculated assuming the packet size to be 133 bytes (or 266 symbols), which is the maximum possible packet size under IEEE 802.15.4. These figures clearly illustrate that the packet error rate quickly deteriorates from 0 to 1 as the SNR deteriorates beyond a threshold. Figures 1(c) and 1(d) present a close up view of the same information focussing on the region of sudden transition in the packet error rate. As these figures show, the packet error rate changes from 0 to 1 as the SNR deteriorates from 1 dB to -3 dB under AWGN model and from 6 dB to -1 dB under Rayleigh fading model. The step-like increase in the packet error rate with SNR deterioration is due to the packet error rate's dependence on the symbol error rate, which in turn depends on the bit error rate. As the figures show, the SNR deterioration results in moderate increase in the bit error rate that causes much steeper increase in the symbol error rate, which in turn causes almost step-like increase in the packet error rate. Thus, we can conclude that the PHY-level packet error rate on an IEEE 802.15.4 link shows a step-like increase from 0 to 1 as the SNR deteriorates beyond a threshold.

5. Conclusion

In this paper, we investigate the relationship between PHY-level packet loss rate and the signal to noise ratio (SNR) in IEEE 802.15.4 networks operating in 2450 MHz range. We demonstrate that, under both additive white gaussian noise and Rayleigh fading models, the packet loss rate increases in a step-like fashion with deterioration in SNR. In other words, PHY-level packet loss rate stays close to zero as long as the SNR is more than a threshold. As SNR deteriorates to this threshold, PHY-level packet loss rate increases to 1 with a small (less than 10 dB; perhaps as small as 4 dB) additional deterioration in SNR.

This result has strong implication regarding the use of SNR (and its faulty indicator RSSI) as a link reliability metric in the operation of routing protocols such as Zigbee and RPL. The SNR should not be used as a fine-grained link reliability metric since the SNR and PHY-level packet loss rate do not share a linear relationship. A certain change in the link SNR may result in no significant change in the PHY-level packet loss rate on the link or it may cause 0-to-1/1-to-0 transition in the PHY-level packet loss rate. An additional problem with the use of SNR as a link reliability metric is the fact that it does not take in account the packet losses occuring at the MAC level. A perfectly reliable link at the PHY level may have poor *layer 3* reliability if it suffers from a high packet loss rate at the MAC level. In CSMA-based protocols such as IEEE 802.15.4, the MAC-level packet loss rate depends on the level of contention for channel access from nodes in the radio range, which in turn depends on the traffic load in that region of the network [8].

We suggest that the *layer 3* reliability of a link be measured in terms of a layer 3 metric that takes in account both PHY-level and MAC-level reliabilities of the link. Layer 3 packet success/loss rate on the link is one such metric. This metric is conceptually simple, independent of the nature of underlying link layer and often the nodes already maintain the information required for its calculation.

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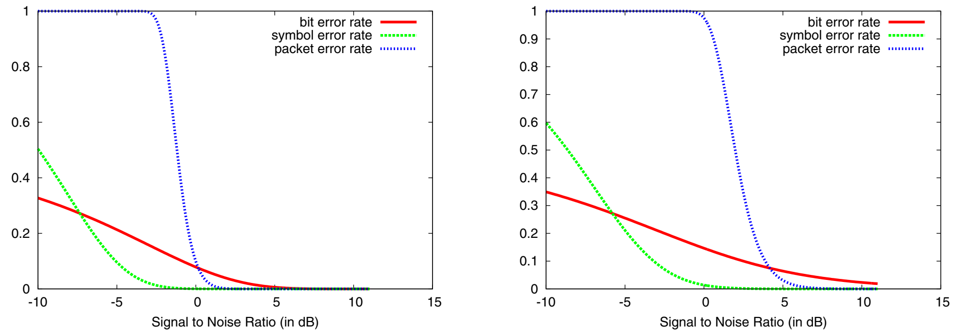
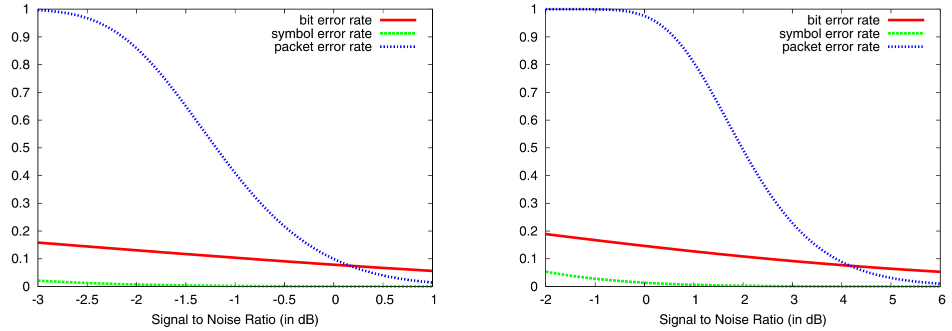


(a) Under Additive White Gaussian Noise (AWGN) model (b) Under Rayleigh fading model



(c) Close up look under AWGN model (d) Close up look under Rayleigh fading model

Figure 1. The impact of SNR deterioration on the bit, symbol and packet error rates for 2450 MHz Operation of IEEE 802.15.4 PHY layer.