Improving Packet Delivery Ratio Estimation for Indoor Ad Hoc and Wireless Sensor Networks

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***Abstract*— Many protocols in wireless sensor networks use Packet Delivery Ratio (PDR) as a metric to select the best route, transmission rate or power. PDR is normally estimated either by counting the number of received hello/data messages in a small period of time, i.e., less than 1 second, or by taking the history of PDR into account. The first method is accurate but requires many packets to be sent, which costs too much energy. The second one is energy efficient, but fails to achieve good accuracy. Therefore in this paper we propose a novel estimation method which takes advantage of receiving signal strength. We show with extensive experimental results that the proposed method is 25% more accurate than the second estimation method, while being simple and energy efficient at the same time.**

I. Introduction

Packet Delivery Ratio (PDR) metric is used by ad-hoc and wireless sensor networks (WSNs) protocols for selecting best routes, optimum transmission rate and/or power between source and destination [1]–[4]. Naturally, wireless link quality in WSNs is subject to environment changes and PDR may vary dramatically over time. Especially in an indoor environment people movement and lack of Line of Sight (LOS) make PDR hard to estimate. Thus a good method is required to timely and accurately estimate PDR in an indoor wireless link.

A straightforward method for PDR estimation is to send a number of hello/data packets in a short period of time. Then the receiver calculated the percentage of the received packets [3]. The estimation results are later transmitted back to the sender so the decisions of changing route or transmission rate can be made. While the impact of PDR estimation on routing is out of scope of this paper, the actual PDR estimation process is. Since nodes in a WSN are powered by batteries and are expected to operate for a long period of time, estimating PDR with a large number of hello packets would consume too much energy. On the other hand, when link quality changes frequently, PDR estimation should be regularly performed, so that route can be adjusted on time for a successful packet delivery. In summary, an ideal PDR estimation method in WSNs should be both timely and energy efficient.

A number of protocols use a moving average function to calculate the current PDR. In this case, unlike in the method that counts only currently received hello messages in a time window, the history of PDR estimation is also considered. However, we will show analytically and via experimental results that although the method is energy efficient, there is a room for improvement in PDR estimation accuracy. As a result, in this paper we propose a novel energy efficient PDR estimation method, which takes the advantage of Receiving Signal Strength Indication (RSSI) measured from every received packet. We will show with experiment results that our method results in improvement of 25% comparing to existing PDR estimation methods discussed above.

This paper is organized as follows. We start with a review of related work in Section II. In Section III we introduce our experimental methodology. Our proposed PDR estimation method and its experimental results are presented in Section IV. Finally the paper is concluded in Section V.

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II. Background and Discussions

Link quality, which refers to PDR in this paper, can be assessed by three essential methods. We introduce them in detail below and analyze their advantages, disadvantages and expected accuracy.

A. PDR Estimation using Received hello Packets

This method does not consider any history in estimation. It sends n packets in a small time window and counts the number of received packets k. Then $PDR_t = \frac{k}{n}$ is the PDR estimation at time window t. We calculate the expected PDR estimation error E_{PDR} for this method as

$$E_{PDR} = \sum_{k=0}^{n} p^k (1-p)^{n-k} \left| p - \frac{k}{n} \right|, \qquad (1)$$

which takes p, the actual (not estimated) PDR value, as a parameter. We assume the time window is very small, i.e., 1 s at most, so that p is constant. Fig. 1 shows E_{PDR} when p changes from 0 to 1. We can see that if $E_{PDR} < 10\%$ is required, we need to send at least 5 hello packets in the time window. Apparently, such an operation is too expensive in resource constraint WSNs.

The purpose of discussing this method is that it is a direct way to "estimate" the actual PDR if n is large. Since the actual PDR can not be obtained, it serves as a good alternative of the actual PDR in evaluating other estimation methods. In the rest of this paper, we will compare the estimation results of other methods to that of this one and the differences are considered as the estimation errors. Although it may drift a little bit from the "actual" estimation error, with a n large enough, the drift should be negligible.

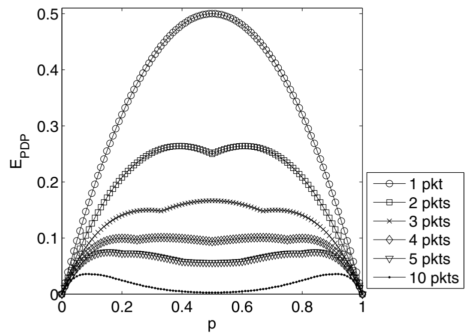


Fig. 1. Expected estimation error E_{PDR} by counting received hello packets versus actual PDR value p.

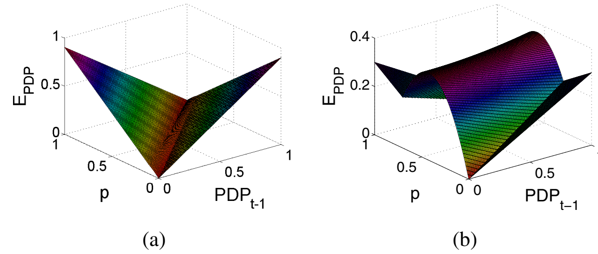


Fig. 2. Expected PDR estimation error E_{PDR} with EWMA estimation for different values of α: (a) $\alpha = 0.1$, (b) $\alpha = 0.7$

B. PDR Estimation using Moving Average Filter

The second way to estimate PDR is to use the Exponential Weighted Moving Average (EWMA) filter, which considers the history of link quality as

$$PDR_t = \alpha Y_t + (1-\alpha)PDR_{t-1}. \qquad (2)$$

Here, PDR_t is the estimated PDR at time t, $Y_t = 1$ represents the correctly received hello packet at time t, $Y_t = 0$ incorrectly received probing packet at time t, and α is the filter parameter. This method requires only one hello packet sent per time window. Certainly in WSNs, hello packets can be substituted by periodical data reporting packet, since many applications require to report every second. Parameter α should be decided properly according to the changes in the link. If the PDR changes very fast, a large α may timely update the estimated PDR. However, when PDR changes slowly, a large α value would result in deviation of the estimated PDR from the actual one.

Similar to the first method, we calculate the expected estimation error as

$$E_{PDR} = p\left|PDR_t(Y_t=1)-p\right|+(1-p)\left|PDR_t(Y_t=0)-p\right|.$$

Fig. 2 shows the E_{PDR} when $\alpha = \{0.1, 0.7\}$. We can see that if the α is small, the expected error of EWMA estimation is fairly small, when S_{t-1} and p are close to each other (the values around the diagonal of the XY plane). As the α increases, the error when S_{t-1} and p largely differ gets smaller, but the error on the diagonal of the XY plane increases. Therefore, the α value has to be carefully tuned.

C. PDR Estimation using RSSI

Many researchers suggested to use RSSI as a link quality indicator, however, they did not quantify precisely the link quality with RSSI. The authors in [5], [6] observed a low correlation between RSSI and PDR when the RSSI was low. It was due to the fact that individual receiver sensitivity and local noise are more dominant factors deciding whether a packet can be received when RSSI is low. Low correlation between RSSI and PDR estimator was also observed when strong multi-path propagation was present [7].

As a summary, the first method is not energy efficient but accurate. The second one induces less overhead, but is less accurate due to parameter α to tune. Finally, the third method may fail to estimate the PDR due to low correlation of PDR and RSSI. Therefore, to find a better method of PDR estimation in an indoor environment, we have conducted experiments to observe the characteristics of PDR. The results are presented in the following section.

III. Experiment Methodology and Observations

A. Experiment Setup

The nodes used in the experiments are t-mote sky sensor motes with 2.4 GHz IEEE 802.15.4 compliant Texas Instruments CC2420 transcievers [8]. The transceiver provides RSSI in a range of 100 dBm for every received packet, which is the received strength signal reading averaged over eight symbol period. The IEEE 802.15.4 packet header is 17 Bytes and the payload is set to 18 Bytes thus a packet is 35 Bytes long. We consider this length as typical for WSN packets. Only one packet length was used in the experiments since in [9] authors have shown that packet size does not affect PDR much in WSN.

We connected the receivers to a PC via wire. Once the receiver received a packet, it reported to the PC the unique packet ID and the RSSI of the packet. The senders transmitted 10 packets every second and we counted how many packets are received. From Section II-A, we expect that sending 10 packets per second should give an accurate estimation of the actual PDR. We tested the wireless links in four typical scenarios as below.

1) *Strong link*: Two nodes were placed about 75 m apart in the corridor of TU Delft Wireless and Mobile Communications Lab, which was about 100 m long and 2 m wide, with offices at either side. There was LOS in the link and a link with high PDR was expected. The packet collection lasted for about 45 minutes.
2) *Weak link*: The experiment was performed on the same corridor as above, however one node was kept in a office and the other in the corridor, thus no LOS existed. The distance between nodes were deliberately tuned to be about 25 m so that the PDR varied a lot in the link. The packet collection lasted for about 2.5 hours.
3) *Mobile link*: Again, the same corridor was used as the experiment environment. The transmitter was placed on

a table in an office and the receiver was carried with walking speed of approximately 1 m/s. The office door were kept open in the experiment. We started from the fixed node and walked out the office with the mobile node to the corridor, where we walked in even pace for 30 m and turned around to go back to the office. At the farthest point the PDR was expected to drop to zero.

4) *Dynamic link*: Sender and receiver were placed in the EEMCS faculty canteen of TU Delft. The packet collection started at 11:00 AM and lasted for 2.5 hours. There was LOS between the nodes, which were placed 20 m apart. However a lot interruptions were expected during the lunch time due to frequent people's movement.

We emphasize that the first three experiments were conducted in a quiet period after working hours. Thus we expected no intensive interruption from the movement of people. Also, in all four experiments, we operated in a 2.4 GHz range absent from WLAN activity to minimize interference from other wireless systems.

B. Observations

From the collected experimental data we draw the following observations.

1) The PDR in strong link is almost 1 for the whole observation time, except for the very beginning when the link was disturbed by people movement. Majority of the RSSI values were between -72 and -74, therefore we conclude that the transceiver can report stable RSSI there.
2) In the weak link the PDR was unstable. The delivery ratio varied from 1 to 0 within a couple of seconds and 50% of the packets were lost in the link.
3) The PDR in the mobile link changed in a repeating pattern. In each period there was a transition, where the delivery ratio changed from high, above 0.9, to low, below 0.1, or vice versa within 5 s.
4) The dynamic link showed two properties. Before the lunch time, from 11:00 to 11:30, the PDR was near 1. However, when people were moving in the canteen during lunch, the link was distorted. From time to time, there were periods when PDR in the dynamic link showed the same characteristics as the weak link.

For each of the links we computed the Allan deviation of PDR, which describes the level of fluctuation between consecutive samples, as

$$A_D = \sqrt{\frac{1}{2y}\sum_{i=2}^{y}(x_i - x_{i-1})^2},$$

where x_i is the sequence of PDR values and y is the total number of samples. From Table I we see that A_D of the dynamic, weak and mobile links are very high compared to the strong link.

We calculate estimated PDR every second, using method described in Section II-A, which we assign to each received packet. For instance, if 5 packets were received in a second,

TABLE I
A_D OF THE PDR IN THE FOUR CONSIDERED EXPERIMENT SCENARIOS

Link Type	A_D
Strong	0.039
Dynamic	0.096
Mobile	0.120
Weak	0.135

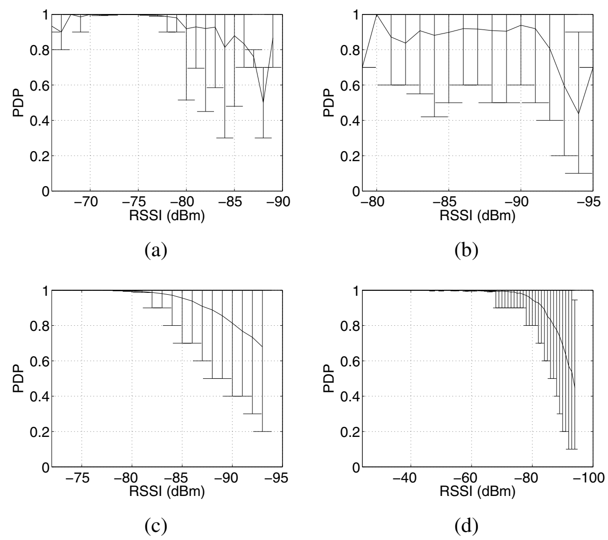


Fig. 3. RSSI to PDR mappings for all considered links: (a) strong, (b) weak, (c) dynamic, and (d) mobile. Here lines represent the average PDR a RSSI maps to, and the bars show the dispersion of the PDRs, of which 90% PDRs are within the bars.

then estimated PDR of the packets is 5/10=0.5. Later the RSSI of a received packet is mapped to its PDR. Fig. 3 shows the RSSI to PDR mapping in the four considered links. Note that the maximum PDR is 1 and the ranges of RSSI on the X axis is different for each scenario. We can see that in the strong link, Fig. 3(a), RSSI from -72 dBm to -74 dBm has average PDR around 1 and the dispersion is very small. It is due to the fact that majority of packets in this link were received within this RSSI range. The rest of RSSI were rarely received, thus have large dispersion in mapping. For the weak link, Fig. 3(b), the range of RSSI is small. When the RSSIs are higher than -91 dBm the average PDR is above 0.9. The dispersion for all the RSSIs are relatively large compared to other link due to the features explained in the second observation above. The dynamic link and mobile link, Fig. 3(c) and Fig. 3(d) respectively, show similar characteristics. In both cases, when RSSI is relatively high, the mean is close to 1 with small dispersion. However, as RSSI decreases, the correlation between RSSI and PDR decreases as well and larger dispersion can be observed.

IV. Proposed PDR Estimation Method

None of the introduced PDR estimation methods works best all the time. For example, the problem for EWMA method is that even if the α value is carefully tuned for a link, it still may have a large estimation error, as shown in

Section II-B. Meanwhile, high RSSIs indicate PDR accurately, but low RSSIs map to too many PDRs to have an accurate estimation. We therefore wonder whether it is possible to exploit the advantages of these methods to get even better PDR estimation.

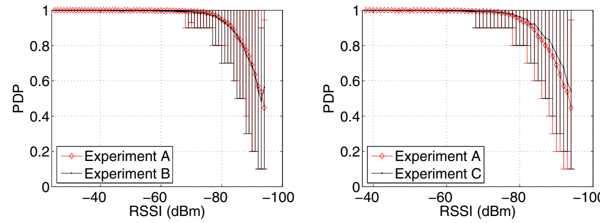
A. Improved PDR Estimation Method

Our new method does not add any extra complexity to the above two methods, while taking the advantages of both of them. The new method estimates PDR with both EWMA and RSSI. However, it decides to trust one rather than another with the following condition

$$PDR = \begin{cases} PDR_t, & \mu - \sigma \le PDR_t \le \mu + \sigma \text{ or no pkt. rcvd.}, \\ \mu, & PDR_t \le \mu - \sigma \text{ or } PDR_t \ge \mu + \sigma, \end{cases}$$

where PDR_t is the PDR estimation by EWMA at time window t given by (2), μ is the average mapped PDR of a RSSI value, and σ is the standard deviation of the mapping. We trust the estimation of EWMA if its difference to the estimation of RSSI is smaller than σ. Otherwise, we take the average value of RSSI to PDR mapping as our estimation. In case that a hello/data packet is not received, no RSSI value is collected so that EWMA estimation is taken. For example, if we have a EWMA estimation of 0.3, when the average of RSSI mapping is 0.8 and the deviation is 0.2. Then we estimate the PDR to the average of 0.8, since 0.8-0.3=0.5>0.2. Although better method may be found in the future, probably with a higher complexity, we will show in Section IV-B that the method can improve the accuracy from both EWMA and RSSI estimation.

A challenge to this new method is to find the mapping from RSSI to PDR and to decide the optimum α. We solve it by carrying out a learning procedure in a representative period of a link. We carried out the learning procedure of the dynamic link between 11:00 and 13:30 since this period from 11:00 to 11:30 represented the "quiet" hours in the link (less people movement in the canteen) and the period from 11:30 to 13:30 represents the "busy" hours in the link (massive people movement in the canteen). In the representative period, a node in the link sends n packets in small windows of time, as described in Section II-A, to measure the approximation of actual PDR, provided that n is sufficiently. Then a packet is randomly chosen from every window. Depending on whether the chosen packets were received, 1 or 0 is input to (2). A series of different α values would be tried until one gave the smallest difference between the estimated PDR and the approximation of actual PDR. Afterwards, each RSSI is mapped to the approximation as described in Section III. Therefore we can have the optimum α and the mapping of the link. Although this learning procedure requires intensive packet transmission, it is negligible because the learned data can be used in the nodes' lifetime of years and the energy spent can be compensated by benefits later. Since the environments where nodes are deployed are different, this learning procedure has to be performed for every individual link. Even in the same link, the environment may change with time thus the optimum



(a) (b)

Fig. 4. Comparison of RSSI to PDR mappings in a mobile link: (a) experiment A vs experiment B, and (b) experiment A vs experiment C (see text for more explanation).

α and mapping may be different. We will evaluate the impact of the difference on estimation accuracy in the next section.

B. Experimental Results

To assess the estimation accuracy of EWMA method, RSSI method and the proposed method, we ran three new experiments in weak link, dynamic link and mobile link. Each experiment was conducted right after the experiments introduced in Section III. The experiment setup was the same and the durations of the experiments were 2.5 hours, 2.5 hours and 1 hours, respectively. We denote the experiments in Section III as 'experiments A' and the new experiments as 'experiments B'. We use the experiments A as the learning procedure to find the optimum α and RSSI to PDR mapping for each scenario. Then we have used them to estimate PDR in the experiments B.

In the B experiments, we also sent 10 packets between the transceiver pair each second. The receiver recorded if packets and RSSIs were received. All the experiment data were processed off-line to evaluate the estimation accuracy. We substitute the actual PDR of each second with its approximation calculated by $\frac{m}{n}$ where n is 10 and m is the number of packets received. Every second, we randomly selected 1 packet out of 10 as the data packet which would be really sent out in actual traffic and practiced the three estimation methods. The estimated PDR was compared to the approximation introduced above. We took the average difference over the whole experiment period as the error of an estimation method, which was used as the metric to evaluate the estimation accuracy.

The optimum α values from the experiments A, which resulted the smallest estimation error of EWMA, are 0.35, 0.39 and 0.39 for weak link, dynamic link and mobile link, respectively. We also checked the optimum α of the B experiments. They were very close to those in experiments A. The differences are smaller than 0.01. It means that the learned α is effective in the following PDR estimations. Similarly, we calculated the RSSI to PDR mapping of the experiments B and compared them to the those of experiments A. The mapping are quite similar to each other. In this paper, we only show the comparison in mobile link in Fig. 4(a) due to space limitations.

After the experiments B, we wanted to check whether the environment changes in a longer time span, i.e., a few weeks,

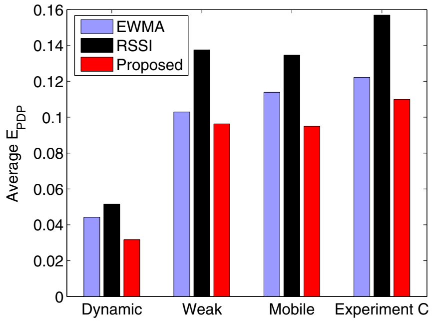


Fig. 5. Comparison of estimation errors of the two existing PDR estimation methods and a proposed one.

would affect the correctness of the learned α and the mapping. Therefore we conducted an additional experiment of mobile link, namely 'experiment C', a few weeks after the above experiments. All the setups and movement pattern were kept same. However, temperature, humidity, doors opening or closing in the corridor and other environmental factors changed. The experiment were also one hour long. Same as above, we have compared the optimum α value and the mapping of experiment C to those of the experiment A. The optimum α was 0.36, slightly lower than that of the A experiment and the comparison of mapping table is shown in Fig. 4(b). We can conclude that, although the two experiments were conducted a few weeks apart, using the α and the mapping table from the experiment A to estimate the PDR in the experiment C is still feasible.

The average estimation errors in the experiments B and C are shown in Fig. 5. Surprisingly, the RSSI method has the largest estimation error in all the experiments. Although the EWMA method takes no information of the signal strength, it estimates the PDR 10% to 20% better than the RSSI method. Therefore we can see that the uncertainty of RSSI to PDR mapping affects the estimation accuracy a lot. The new method improves the estimation accuracy from the other two methods in all the experiment. It achieved the largest improvement of 25% to EWMA method in the dynamic link. Contrarily, there is only 5% improvement in the weak link. The reason is that majority of the packets delivered in the weak link are received with low RSSIs, which have large deviation of mapping to PDR. The estimation in the two mobile links shows some differences. In the experiment B, the new method shows 17% improvement from the EWMA method. However, the improvement in the C experiment is only 10% due to the slightly changed mapping. All the three estimation methods were less accurate compared to those in the experiment B because of the sub-optimized α and the differences in mapping. However, the performance degradation was not fatal.

V. Conclusions

Link quality assessment, which refers to Packet Delivery Ratio (PDR) estimation in this paper, is an important subject in reliability research for Ad Hoc and WSNs. In this paper, we have discussed existing PDR estimation methods and concluded that they are either energy consuming or inaccurate. To mitigate these issues we have proposed a new method which exploits the advantages of estimation methods based on Exponential Weighted Moving Average (EWMA) method and Received Strength Signal Indication (RSSI). The optimum weighting factor α and the mapping of RSSI to PDR were learned from representative experiments. In each pre-defined period of time, this new method decides to trust the estimation result either from the EMWA method or the RSSI method, depending on which of them is more accurate. We show with experimental results that the new proposed method improves the estimation accuracy by up to 25% compared to existing EWMA method.

A potential problem in this new method is the drifts of the optimum α and the RSSI to PDR mapping along time. From the two experiments which were conducted few weeks apart, we could see that the optimum α and the mapping changed slightly. Although the difference did not affect the estimation accuracy too much in our experiments, larger changes could degrade the accuracy more. Therefore we might have to update the optimum α and the mapping periodically. It means a machine learning mechanism has to be implemented in nodes so that environment changes along time can be taken account in PDR estimations. Besides, it would be also interesting to know how the improved PDR estimation help MAC or networking protocols to perform better, i.e. larger throughput. We are currently working on these subjects.

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