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Channel Ranking Based on Packet Delivery Ratio Estimation in Wireless Sensor Networks

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Abstract—**Wireless sensor networks (WSNs) operating in 2.4 GHz unlicensed bands must explore favorable channels in order to mitigate the effects of induced interference by co-existing wireless systems and frequency selective fading. In this context, we develop a packet delivery ratio (PDR) estimation method for channel ranking in WSNs. The PDR, in general, is defined as a function of signal-to-noise ratio (SNR) and signal-to-interference-plus-noise ratio (SINR) at the sensor and the packet collision-time distribution of the sensor link. The collision-time distribution depends on the packet size and packet inter-arrival time distributions of both networks. Under limited channel measurements, the collision-time cannot be estimated satisfactorily. In order to bypass the collision-time estimation process, the proposed PDR estimation method utilizes signal level, interference and noise characteristics identified by spectrum measurements adjusted to the intended traffic pattern of the sensor link. The proposed method is validated against the empirical PDR using off-the-shelf sensor platform in emulated multipath wireless fading channels. The results reveal that the method is accurate in modeling the empirical PDR with limited channel energy measurements. In addition, we used the estimated PDR as a metric for channel ranking and verified its effectiveness by ranking the available channels to a WSN under interference from multiple WLANs in a real environment.**

Index Terms—**Wireless sensor network, wireless LAN, co-existence, packet delivery ratio, channel ranking**

I. INTRODUCTION

Wireless sensor networks (WSNs) have emerged as a promising low-cost technology to establish flexible networks in 2.4 GHz unlicensed band for monitoring and control applications. The main threats to the communication reliability of WSNs are interference from coexisting wireless systems and frequency selective fading. The communication reliability in such hostile environment can be enhanced by adjusting the network operation on favorable channels determined by a channel ranking scheme [1], [2], [3]. The channel ranking is the ordering of the available WSN channels according to a performance metric such as interference strength and/or activity factor, packet delivery ratio (PDR).

In this paper, we develop a PDR estimation method for channel ranking in WSNs. The PDR as a performance metric for channel ranking is appreciated since it combines the effect of temporal and spatial dynamics of the co-existing systems [1]. The PDR estimation by counting the successfully received probe packets is energy inefficient for channel ranking. Theoretically, PDR is defined as a function of SNR, SINR and collision-time distribution of a sensor link [4]. The collision-time distribution depends on the traffic pattern; the packet sizes and packet inter-arrival distributions of two co-existing systems under study. The PDR estimation, using this model, requires finding the signal and interference level estimates, and the collision-time distribution. This model is used by [1], [5] to estimate PDR at a WSN receiver using channel energy measurements. However, in [1], PDR is estimated by assuming traffic patterns which set bounds on the channel ranking error, whereas, the effect of traffic pattern on PDR estimation is ignored in [5].

The existing channel ranking schemes are based on the identification and utilization of the interference characteristics, activity factor and/or interference level estimates [1], [2], [3], [5]. These interference characteristics are determined by channel energy measurements. In [2], channels are ranked only based on the activity factor estimate. In [3], the ranking scheme is based on a heuristic combination of activity factor and interference level estimates. In [1], [5], channel ranking is based on PDR estimation. However, in [1] instead of estimating the exact PDR, a traffic pattern setting up the upper bound on ranking error is utilized for ranking the channels. In [5], instead of channel ranking, the first channel satisfying a certain PDR target is selected. Moreover, by assuming the sensor link strength is the same over all channels, the cited previous studies only consider the interference characteristics for ranking. As shown in [6], there is a significant frequency selective fading in 2.4 GHz band. In this situation, a least interfered channel might not provide the best channel quality.

In this paper, PDR estimation method for channel ranking is designed such that:

- Interference characteristics are taken into account using limited channel energy measurements such that traffic pattern estimation is avoided.
- The effect of multipath fading on the interfering signal is considered.
- Signal level variations in the sensor link across available channels are considered.

In order to bypass the traffic pattern estimation, we design a spectrum measurements scheme in which a sensor node collects energy samples from a channel according to the intended packet size and inter-arrival distribution of the sensor link. In this scheme, a set of successive channel energy samples with measurement time equal to packet transmission time is called a macro-sample, while a single channel energy sample is called a micro-sample. Each micro-sample contains average channel energy over certain number of packet bits. The PDR is estimated as an average over multiple macro-samples, collected at the packet inter-arrival times, where a packet success is achieved as the product of success probability of bits in all micro-samples belonging to a macro-sample. The success probability of bits is obtained by translating SINR, which is obtained from the signal level of the sensor link and the micro-sample energy, into a given bit error rate. The signal level of the link is obtained by transmitting probe packets. Based on this formulation,

- The estimated PDR is validated against the empirical PDR using off-the-shelf sensor platform in emulated multi-path wireless fading channels.
- The optimum number of channel samples is identified to accurately estimate the PDR.
- The effectiveness of PDR estimation for channel ranking is verified by sorting the available WSN channels in 2.4 GHz band under interference from multiple WLANs in a real environment.

The rest of the paper is organized as follows. Section II introduces system model, channel sensing and PDR estimation schemes. The proposed PDR estimation scheme is evaluated experimentally in Section III and its performance for channel ranking in a real environment is given in Section IV. Finally, the conclusions are drawn in Section V.

II. SYSTEM MODEL

We consider a single wireless sensor link established between two sensor nodes acting as transmitter (S_{tx}) and receiver (S_{rx}). These nodes can be assumed to be a part of a WSN operating at 2.4 GHz unlicensed band partitioned into K channels ($c = 1, 2, ..., K$). The same spectrum is used by co-existing WLAN(s) with overlapping but different channel partitioning. The WLAN(s) communication on these channels induces interference to the sensor link. The considered scenario is shown in Fig. 1 where I_c and ρ_c are the perceived interference level and activity factor at the WSN receiver, and S_c is the sensor link strength on channel c. The receiver node estimates the S_c with some probe packets since the received signal level on each channel may be different due to frequency selective fading. The WSN receiver ranks the available channels based on the PDR estimates achieved using S_c and channel energy measurements.

A. Channel Measurements and PDR Estimation

In order to estimate PDR without estimating the interference traffic distribution, we set the channel measurements time according to the intended traffic from the transmitter node. We assume that S_{tx} intends to send N-bit packets periodically at a rate of P packets/sec. Each packet is transmitted at a fixed data rate of R bits/sec. This is a typical WSN traffic model where sensors periodically report data to the sink.

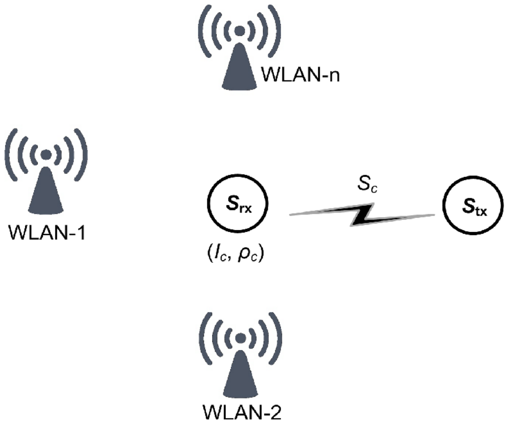


Fig. 1. Considered scenario: Coexisting WSN link and WLAN(s)

A receiver collects L macro-samples $X_c^1, X_c^2, ..., X_c^L$ on a channel with time spacing of $T_I = 1/P$ in order to identify the noise and interference characteristics. Each macro-sample consists of ℓ micro-samples uniformly distributed over the packet transmission time $T_s = N/R$. Figure 2 shows the described channel measurement scheme where $x_c^{i,j}$ indicates the jth collected micro-sample in ith macro-sample on channel c. These channel samples are collected by using the default energy detector (ED) of the sensor radio chip. The ED provides the received energy on a channel regardless of the signal type. In the absence of WLAN interference, the reported energy sample contains pure noise, otherwise, it contains the WLAN signal embedded in noise.

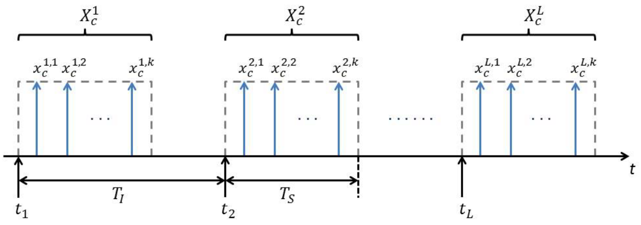


Fig. 2. Channel energy measurements scheme

We assume that the WSN is based on the IEEE 802.15.4 standard [7]. The PHY layer of IEEE 802.15.4 uses offset quadrature phase shift keying (OQPSK) modulation with half-sine pulse shaping, which is equivalent to MSK modulation [8]. The bit error rate (BER) of OQPSK modulation in additive white Gaussian noise (AWGN) channel is $Q\left(\sqrt{2kE_b/N_0}\right)$, where $k \approx 0.85$ [9] and E_b/N_0 is the ratio of the average energy per information bit to the noise power spectral density at the receiver input. The E_b/N_0 is equivalent to SNR $= S_c/P_N$ or SINR $= S_c/\left(I_c + P_N\right)$ depending on interference absence or presence respectively, where P_N is the noise power.

Given that the bit errors occur independent of each other, for a N-bit packet the PDR can be calculated by considering the probabilities of receiving all the individual bits correctly

$$\mathrm{PDR} = \prod_{i=1}^{N} \left(1 - Q\left(\sqrt{2k\mathrm{SINR}^{i}}\right)\right) \tag{1}$$

where SINR^i is the SINR corresponding to the ith bit of the packet.

Assuming the link strength on a given channel (S_c) is known, we can define $\mathrm{SINR}_c^{i,j}$ in dB as the difference between S_c and energy sample $x_c^{i,j}$ as [3]

$$\mathrm{SINR}_c^{i,j} = S_c - x_c^{i,j} \tag{2}$$

As per the assumptions, $\mathrm{SINR}_c^{i,j}$ represents the SINR at the receiver corresponding to the jth bit belonging to the ith packet. If the interference is changing slowly within the time-gap between two consecutive micro-samples, the SINR for N/ℓ consecutive bits can be assumed to be the same. In this case, the PDR considering only the ith macro-sample can be expressed as

$$\mathrm{PDR}_c(i) = \prod_{j=1}^{\ell} \left(1 - Q\left(\sqrt{2k\mathrm{SINR}_c^{i,j}}\right)\right)^{\left(\frac{N}{\ell}\right)} \tag{3}$$

The PDR estimate can be obtained by averaging Eq.(3) over L collected macro-samples

$$\mathrm{PDR}_c = \frac{1}{L}\sum_{i=1}^{L}\prod_{j=1}^{\ell} \left(1 - Q\left(\sqrt{2k\mathrm{SINR}_c^{i,j}}\right)\right)^{\left(\frac{N}{\ell}\right)}. \tag{4}$$

III. EXPERIMENTAL EVALUATION

We designed an experimental setup to assess the accuracy of PDR estimation model given in Eq.(4) under WLAN interference. The experimental setup measures the empirical packet delivery of a sensor link under the emulated LOS/NLOS indoor multi-path propagation conditions of the interfering signal. In the same environment, the receiver node collects channel samples to estimate the PDR.

A. Experimental Setup

The sensor nodes are based on Sensinode micro-series platform employing Texas Instrument MSP430 micro-controller and Chipcon CC2420 radio transceiver [3]. A PC equipped with a TP-Link TL-WN651G 802.11(b/g) PCI wireless adapter is used as WLAN interfering node. The PCI adapter is Atheros chipset, supported by MadWifi driver [10]. The WLAN node generates different traffic distributions with MGEN v.5.02 [11].

The built-in antenna of the sensor nodes are broken off and replaced by SubMiniature version A (SMA) connector to establish a wired connection. The signal from the WLAN interferer is passed through a channel of the EB Propsim C8 channel emulator [12] and undergoes fading according to one of the channel models proposed by Medbo and P.Schramn [13], [14]. The faded WLAN signal is then combined with signal from the transmitter sensor node before its reception at the receiver sensor node. This complete experimental setup is shown in Fig. 3.

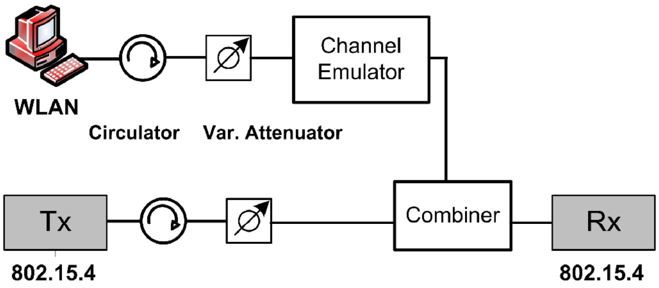


Fig. 3. Test bed for experimental evaluation

B. Experimental Methodology

The WLAN node generates UDP packets in multi-cast mode. Each packet is transmitted at a constant output power and at a PHY rate of 11 Mbits/s. The WLAN node generates the packets periodically, with a nominal packet size of 500 bytes and at a fixed rate of 100 or 700 packets/sec. On the other hand, we consider that the transmitter node intends to transmit packets every 30 $m$sec. The total packet size including headers is 62 bytes which corresponds to 1.984 $m$sec of packet transmission time. The WLAN and WSN nodes operate on frequency channels such that there is 2 MHz offset between their center frequencies.

The receiver node calculates the PDR empirically as a ratio of successfully received packets to the 1000 transmitted packets. In addition, it records the received signal strength indicator (RSSI) value of each received packet and after that it collects an RSSI sample from the channel. The collected channel samples are compared with a threshold (γ) to distinguish if it is noise or interference. The mean SINR is calculated by using the difference between average RSSI value of received packets and the average of the samples exceeding the threshold. The signal energy from transmitter node is changed with the aid of an attenuator and packet transmissions are repeated to obtain PDR ranging from the minimum possible value to 100%.

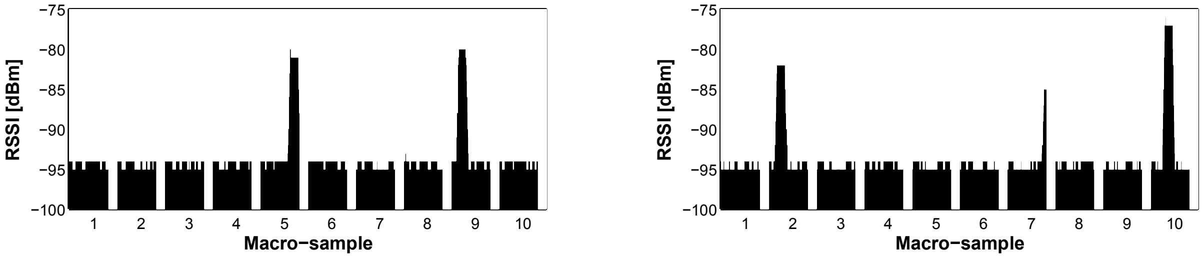
In order to differentiate between interference and noise samples, each sample is compared with the threshold γ

$$x_c^{i,j} \underset{\text{noise}}{\overset{\text{interference}}{\gtrless}} \gamma \tag{5}$$

A channel sample collected by the default ED gives the average received signal strength over 8 symbol periods i.e. over 256 samples [1]. Therefore, for a given probability of misinterpreting noise from an interfering signal that is the probability of false alarm, the threshold can be calculated from Eq.(6) [15].

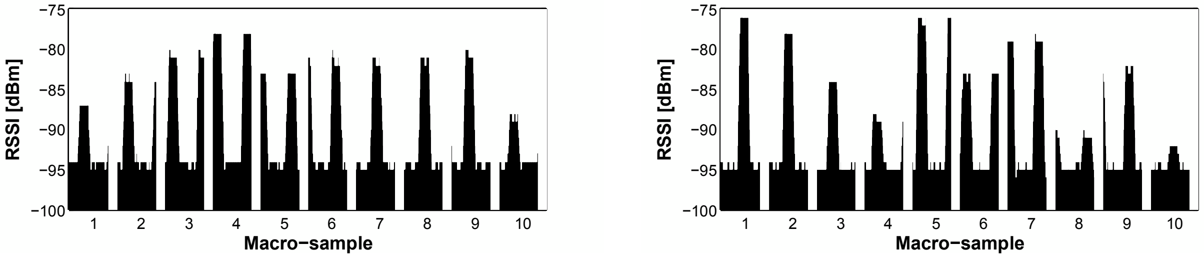
$$\mathrm{Pr}_{fa} = \frac{1}{2}\mathrm{erfc}\left(\frac{\gamma - P_N}{\sqrt{2P_N^2}}\right) \tag{6}$$

For a given channel model and packet rate of WLAN transmitter, the receiver node performs channel measurements by keeping the transmitter node silent. According to the assumed traffic pattern from the transmitter node, the receiver node adjusts channel measurement parameters such that the time spacing among macro-samples is $T_I = 30$ $m$sec and a



(a) LOS, 100 packets/sec

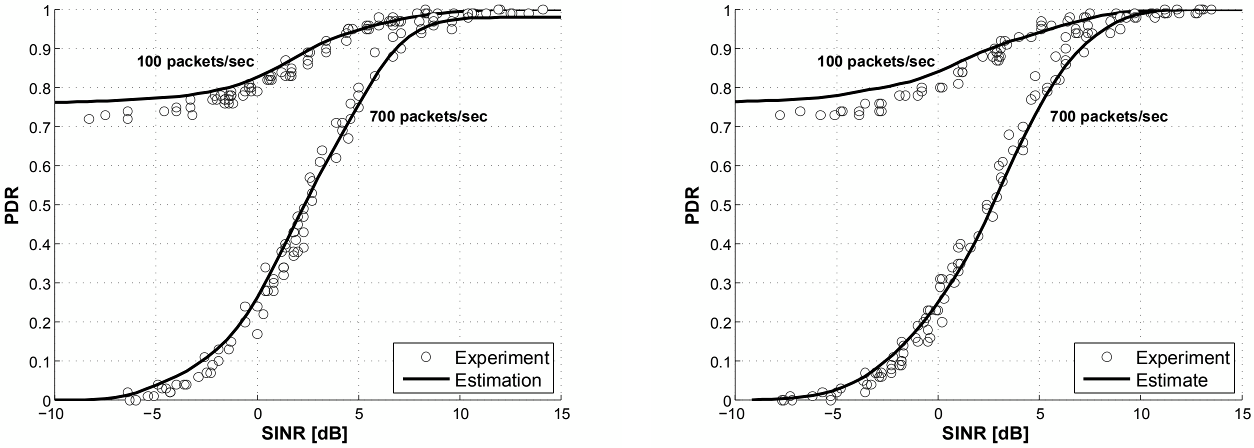
(c) NLOS, 100 packets/sec



(b) LOS, 700 packets/sec

(d) NLOS, 700 packets/sec

Fig. 4. Captured macro-samples under WLAN interference with different packets/sec in various channel conditions



(a) LOS, 100 / 700 packets/sec

(b) NLOS, 100 / 700 packets/sec

Fig. 5. Empirical and estimated PDR under WLAN interference with different packets/sec in various channel conditions

macro-sample measurement time is $T_s = 1.984$ $m$sec. Since the RSSI value is reported over 8 symbol periods ($t_s = 128$ μsec), a macro-sample contains 16 non-overlapping micro-samples (i.e. $T_s/t_s \approx 16$).

C. Experimental Observations

The PDR of the sensor link is measured empirically and compared with its estimated value under different interferer packet rates and wireless channel models. Two single-input single-output (SISO) WLAN channel model A and channel model D [13], [14] are defined separately for the channel emulator modeling fading for interfering signal in non-line-of-sight (NLOS) and line-of-sight (LOS) channel conditions respectively.

The receiver node performs the channel measurements according to the intended traffic pattern from the transmitter node under different interference conditions. The first ten macro-samples collected from each interferer condition are plotted in Fig. 4. The following facts can be observed from these figures:

- The noise level is around -98 dBm as indicated by the low RSSI values whereas the RSSI values greater than the threshold ($\gamma = -92$ dBm, considering $P_N = -98$ dBm and $\mathrm{Pr}_{fa} < 10^{-4}$) represent the perceived WLAN interference strength.
- For each channel model, as the WLAN packet rate is increased, samples containing the interference are increased. For example, under 700 packets/sec, all macro-samples are contaminated by interference and even some of the macro-samples indicate transmission of more than one interfering packets in the measurement period.

- The variations in the perceived interference energy are caused by the channel fading which are more evident in NLOS condition than LOS condition.

The estimated PDR using 100 macro-samples and the empirical PDR are compared in Fig. 5. From this figure, it can be observed that the estimated PDR closely follows the empirical PDR and the error is almost less than 5% in all interference conditions. The PDR results are presented as a function of average SINR, i.e. the difference between the average received signal strength and average perceived interference and noise energy. In addition, the transmitter node signal strength in all of these experiments is kept such that the SNR is greater than 10 dB. Conseqently, the receiver node can receive all the interference-free packets correctly. This condition clarifies the relationship between the lowest PDR and the interference-free macro-samples for any interference packet rate. The PDR under interference with 100 packets/sec starts at around 80% (Fig. 5) which corresponds to 8 out of 10 interference-free macro-samples (Fig. 4.a & c). For a packet rate of 700 packets/sec, PDR starts from 0% (Fig. 5) since all the macro-samples are collided with packet tranmissions from the interferer (Fig. 4.b & d).

Increasing the number of channel samples enhances the accuracy of the PDR estimation at the cost of more energy consumption during the sensing procedure. The adequate number of channel samples ensures that the effects of the interference traffic and fading are taken into account properly in the estimation. In order to ascertain the minimum required number of channel samples, we estimated the PDR for 700 packets/sec from interferer in NLOS condition using different number of macro-samples. Figure 6 clearly shows that the PDR estimation accuracy is low with 20 macro-samples, especially when the SINR is low. On the other hand, the PDR estimate with 40 macro-samples follows the experimental results closely and insignificant improvement is observed with 60 macro-samples.

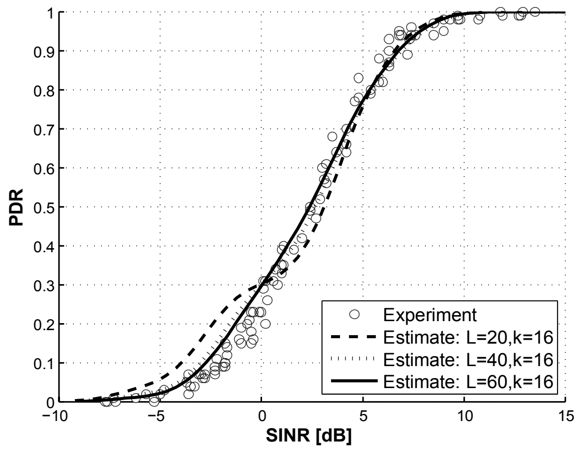


Fig. 6. Empirical and estimated PDR based on different number of macro-samples

IV. CHANNEL RANKING IN REAL ENVIRONMENT

In order to evaluate the capability of the proposed PDR estimation model for channel ranking, we performed an experiment in a realistic multiple WLANs co-existence environment. A LOS sensor link was established between two sensor nodes in an indoor office room at the Communication and Networking department of Aalto University. The link was subjected to interference by co-located WLANs communication on the considered spectrum. Figure 7 shows a snapshot of the instantaneous and average WLAN(s) interference level perceived by the receiver sensor node. In this environment, we considered ranking all 16 available channels based on the estimated PDR at the receiver node.

For estimating PDR on each channel, at first the transmitter node sent 10 packets and the receiver node recorded the RSSI value of each successfully received packet. The average of these RSSI values was considered as the average received signal strength of the sensor link on the channel. On a given channel, the signal strength did not vary much, however, it varied considerably across channels (see Fig. 8). The receiver node then collected 40 macro-samples from the channel according to the intended traffic from the transmitter node; i.e. periodic traffic with packet payload size of 62 bytes packet and packet inter-arrival time of 30 $m$sec. The receiver node then predicted the PDR on the channel using the proposed PDR estimation method. After scanning a channel, 1000 packets were transmitted to measure the empirical PDR on the channel. These steps were repeated for all 16 channels and they were sorted according to their estimated and empirical PDRs. The estimated and empirical channel ranks are given in TABLE I.

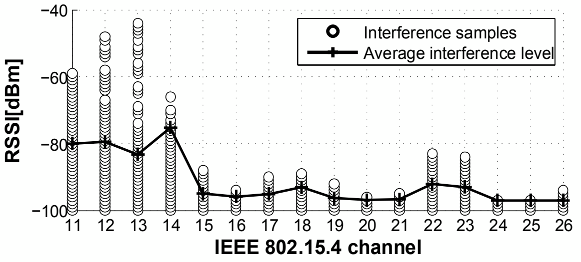


Fig. 7. Interference strength on the candidate channels

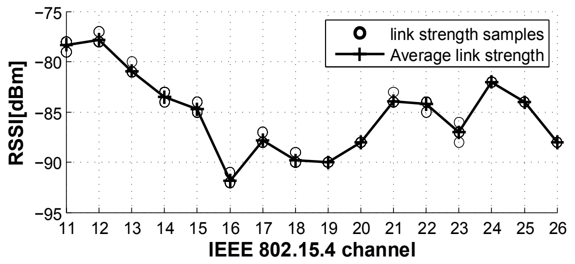


Fig. 8. Received signal strength on the candidate channels

TABLE I
CHANNEL RANKING BASED ON PDR ESTIMATION AND EMPIRICAL PDR

	PDR		Channel Rank	
Channel #	Experiment	Estimate	Experiment	Estimate
11	70	78	16	15
12	71	76	15	16
13	76	79	14	14
14	78	80	13	13
15	99	99	6	6
16	97	96	8	8
17	97	95	9	9
18	86	82	12	12
19	99	99	7	7
20	100	100	1	1
21	100	100	2	2
22	90	95	10	10
23	90	90	11	11
24	100	100	3	3
25	100	100	4	4
26	100	100	5	5

It can be seen from TABLE I, the ranking method based on PDR estimation can sort the channels almost correctly with one exception; the two worst channels with achievable PDRs of 70% and 71% are misplaced. This minor mistake is made since these channels had very close PDRs.

V. CONCLUSION

In this paper, a simple yet effective PDR estimation method based on passive channel measurements is proposed to rank the candidate channels in wireless sensor networks. The proposed method does not rely on the prior knowledge or estimation of the traffic patterns of other competitive users, instead the channel measurements are adjusted according to the sensor link traffic. The optimum number of channel samples is determined to minimize the energy consumption providing the required accuracy. The PDR estimates in emulated and realistic channel conditions are in good agreement with the empirical PDR results suggesting that the proposed method can be effectively used for channel ranking. In a large sensor network with the same traffic pattern for all nodes, a particular receiver node needs to perform the channel measurements procedure only once for each channel to determine PDR estimates for different links. By using the link strengths from neighbor nodes and a single set of energy measurements, the PDR estimates on a channel for all the links can be determined.

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