A Link Quality Estimation Model for Energy-Efficient Wireless Sensor Networks

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***Abstract*—Understanding fluctuations of link quality in a wireless sensor network is useful for different reasons. For example, nodes can determine when and for how long they should transmit packets, so that they can reduce packet loss rate and the cost of retransmission (delay as well as power consumption). However, because the quality of a link depends on many factors, it cannot be known except in a probabilistic sense. In this paper we estimate the expected duration in which the quality of a specific link remains stable using the conditional distribution function of the signal-to-noise ratio (SNR) of received acknowledgment packets. We employ the expected duration to determine how long nodes should transmit packet in burst and how long they should refrain from contention. To develop our model, we deployed Imote2 sensor platforms in indoor and outdoor places and transmitted more than 70, 000 packets. We transmitted additional 16,900 packets to test our model. 90% of the time, our approach resulted in high packet delivery compared with the case in which packets were transmitted without knowledge of link quality fluctuations.**

***Index Terms*—Bursty links, burst transmission, link quality estimation, transmission control, wireless sensor networks**

I. INTRODUCTION

The scope and application of wireless sensor networks is significantly different from other types of wireless networks such as wireless local area networks and ad hoc networks. Whereas the latter are used by many users and many applications, wireless sensor networks are deployed mainly with a single application or even a single sensing task in mind. Moreover, the nodes associated with the latter networks can be charged almost on a daily basis while this is not the case for wireless sensor nodes. In fact these nodes should spend much of the time in a sleeping state to save energy, because they have to operate for a long time without charging or replacing their batteries.

One of the factors which considerably affect the performance as well as the lifetime of wireless sensor networks is link quality fluctuation. Link quality fluctuation can reduce throughput, increase packet delivery latency and jitter, and cost energy due to the retransmission of lost or corrupted packets. This is particularly true for wireless sensor networks which are deployed in harsh environments. The term “harsh” should be understood broadly, for many urban deployments (such as for traffic monitoring, pipeline monitoring, structural health monitoring) where human and car movements are frequented can experience a large packet loss rate [1].

Commercially available radio chips, such as CC2420, provide a summary of the link quality (RSSI and LQI) by evaluating incoming packets and make this information available to the MAC and higher-layer protocols. This knowledge can be useful in a variety of ways. For example,

- MAC layer protocols can take advantage of this knowledge to save energy, for example, by defining an optimal duty cycle.
- Applications can define a higher-level power management policy that takes the quality of a link into account, for example, whether packets should be transmitted in burst, whether lost packets should be retransmitted, or whether packet loss can be tolerated to a certain extent.
- If packets should be transmitted in burst, then knowledge of the link quality can be useful for determining the size of a burst.
- In a multi-hop communication, MAC layer protocols can autonomously decide to which neighbor packets should be forwarded.

In most real-world deployments, the quality of a link cannot be known in a deterministic sense and should be modeled as a random process. Statistics pertaining to this process can be obtained directly from the link quality estimation metrics. Because the lifetime of typical wireless sensor networks should be long, sufficient statistics can be gathered from incoming data and acknowledgment packets. An interesting task would be to identify periodicity in the fluctuation of the link quality so that application can determine when to transmit packets and when to refrain from transmitting. To be sure periodicity in a strict sense is difficult to determine because the factors that affect the quality of a link are so diverse. Instead, one can define periodicity in the mean square sense.

For a time varying random process, $\mathbf{l}(t)$, the mean square periodicity can be expressed as [2]:

$$E\left\{(\mathbf{l}(t+T)-\mathbf{l}(t))^2\right\}=0 \tag{1}$$

where T is the period. The autocorrelation of such a process must be doubly periodic:

$$R(t_1 + mT, t_2 + nT) = R(t_1, t_2) \tag{2}$$

where t_1 and t_2 are two arbitrary time instances and m and n are two arbitrary integers. It should be noted that periodicity in the mean square sense does not require that the process should be strictly periodic with period T and probability of 1.

The difficulty of this approach is its demand to determine both R and T. If, on the other hand, **l**(t) can be considered statistically stationary (at least in a wider sense), then it suffices to observe the process for a certain period of time to obtain the distribution or the density function and with it to determine T. In this paper we propose a lightweight approach to determine the periodicity of a link quality fluctuation in the mean-square sense and experimentally demonstrate how it can be used to compute the number of packets that can be successfully transmitted in burst.

Whereas link quality estimation has been studied in the past in different contexts [3] [4] , to the best of our knowledge ours is the first to determine periodicity and to use the result for computing an optimal burst size. Our approach can also be useful for determining optimal duty cycles, though the focus of this paper is not on duty cycle.

The rest of this paper is organized as follows: In Section II, we describe related work on link quality estimation and on measurement and analysis of burstiness. In Section III, we present experimentally obtained data and analyze them to identify the relevant parameters that can help us identify periodicity in link quality fluctuation. In Section IV, we introduce our approach to determine periodicity. In Section V we provide quantitative results and evaluate their implication. Finally in Section VI, we provide concluding remarks and outline future work.

II. RELATED WORK

Several empirical studies exist on characterizing link quality fluctuation and on link quality estimation [5], [6], [7], [8]. These studies broadly classify a link as (a) connected, where links are highly reliable, symmetric and stable, (b) transitional (intermediate), where links suffer from frequent fluctuations in quality and, hence, they are considered as unreliable and bursty, and (c) disconnected, where links are of very poor quality and communication is not possible. The metrics they use for classification are, among others, packet reception rate and acknowledgment reception rate. In connected links packets can be transmitted with a high probability ($> 90\%$) and in disconnected links packet can be transmitted with a low probability ($> 10\%$). In an intermediate link, however, packet/acknowledgment reception rate is a random variable and the relationship between packet reception rate and any of the link quality parameters (RSSI, LQI, SNR) is never deterministic. Most of the studies assert that typical wireless channels describe the intermediate link [5], [9], [10].

The adaptive transmission power control (ATPC) of Lin et al. [11] employs a closed-loop feedback system to compensate for link fluctuation in the intermediate region. Based on an empirical study, the authors establish a correlation between transmission power and link quality. Their aim is to reduce the overall energy consumption by adapting the transmission power to the minimum level necessary for a successful packet delivery.

Alizai et al. [6] study the short term variation of wireless links in order to identify short-term stable periods in a bursty link. They use the temporary stable links for multi-hop communication. Similarly, Rusak et. al. [9] investigate the time varying characteristics of wireless channels at the physical and link layers. They observe that packet reception rate (PRR) changes over time suggesting that at different time scales the channels are best characterized as bursty rather than stable. They apply wavelet transform on received signal strength indicators (RSSI) for analyzing and characterizing the burstiness of the channels. They observe that burst periods repeat themselves and have self-similar nature.

Srinivasan et al. [5] propose a β metric to measure the burstiness of a link. The β factor is a measure of how close a link is to an ideal link. It is calculated by using the Kantorovich-Wasserstein (KW) distance [12], which measures the distance between a conditional probability delivery function (CPDF) of a given link with an ideal link. The CPDF expresses the probability of receiving the next packet successfully after n consecutive successes or failures. The value of β determines the burstiness of the link. A $\beta = 1$ represents a perfect link and $\beta = 0$ represents an uncorrelated link. To explore the performance of the β metric, the authors propose a transmission control scheme which is intended to increase the packet reception ratio by sending packets in bursts until they encounter a failure. When a failure is detected, transmission is halted for 500 ms. The limitation of this approach is the large amount of data the algorithm requires to predict the success of the next packet.

Munir et al. [13], propose a scheduling algorithm which produces latency bound for real-time periodic streams for burst links. The authors define the burst period as a period of continuous packet loss and use a metric called Bmax to compute this. They perform an empirical study for 21 days and collect data from different links. For each link they transmitted over 3 million packets and recorded the data trace of success and failure which is used to compute Bmax. The algorithm is used off-line. Likewise, Brown et al. [14] introduce BrustProbe, a mechanism to measure link burstiness online. Probing slots, embedded transmission schedule to access link burstiness online, are shared between neighbors. The probe mechanism is more reactive for capturing burst period due to online probe sharing, but it increases the energy consumption and duty cycle by 2%.

III. APPROACH

The contention-based MAC protocols in wireless sensor networks are designed by taking the uniqueness and limitations of the networks into account [15]. For example, most of them avoid the use of control packets (RTS and CTS) by assuming that collision is a rare occurrence, because packets are generated and transmitted infrequently (if collisions occur, then packets are retransmitted). Similarly, they define duty cycles for nodes to sleep much of the time. Nevertheless, these protocols also force nodes to contend for the medium for each packet they transmit. As long as the assumption concerning the packet generation and transmission rates holds, contention for each packet is acceptable, but when the assumption is no longer valid, the throughput of these protocols becomes a significant bottleneck.

More recently, a new batch of MAC protocols has been proposed to enable bulk data transfer, and, thereby, achieve high throughput [16], [17]. The idea is to enable nodes transmit multiple packets in burst once they have won a medium. These protocols disregard fairness because they assume that a wireless sensor network belongs to a single application and a node that has interesting data should have priority. Even when data have to be gathered from each node with equal proportion, burst transmission avoids aimless contention and enables nodes to sleep longer.

One essential question that has not been sufficiently addressed concerning burst transmission is determining the size of a burst. Addressing this question is important because burst transmission cannot go on endlessly. Secondly, contending nodes should estimate how long a burst transmission lasts, so that they can attempt to win the medium at the right time. Thirdly, the efficiency of burst transmission depends on how the quality of a link fluctuates. The longer the transmission ends, the more likely the quality of a link fluctuates, which means the probability of unsuccessfully transmitting packets becomes high and, hence, the cost (both delay and energy) of retransmission becomes high as well.

In this paper, we aim to determine the appropriate size of a burst by taking the statistics of link quality fluctuation into consideration. We identify stable regions during packet transmissions and describe the durations of these regions using a CDF. Once the CDF of a given region is known, then it is possible to determine the expected duration of this region. The objective is to tailor the burst size to the duration of a region which most likely characterize a link.

In order to investigate how the quality of a link fluctuates and to identify the appropriate metrics that can describe the quality of a link, we deployed IMote2 sensor platforms (which integrate the CC2420 radio) in different locations (both outdoors and indoors) and transmitted packets continuously. We considered different distances between a transmitter and a receiver as well as different transmission power levels. Table I summarizes some of the parameters we included in our experiment set up. Altogether we transmitted 70,000 packets. For management reasons, we inserted a 20 ms (during the transmission of 30,000 packets) and a 100 ms (during the transmission of 5000 packets) inter-packet transmission interval during transmission.

For a 0 dBm transmission power, we varied the distance between the transmitter and the receiver in 2 m interval from 1 m to 35 m, until the link was totally disconnected. For a -10 dBm transmission power, we varied the separation distance from 5 to 17 m in intervals of 2 and 5 m. No lost packet was retransmitted. A packet transmission was considered successful when the transmitter received an ACK packet. Otherwise it was marked as failed. From the successfully received ACK packets, we estimated the Acknowledgment Reception Rate (ARR) [1].

TABLE I: Summary of the experiment set up for characterizing the fluctuation of link quality.

Location	indoor, outdoors
Successively transmitted packets	5000, 30,000
Overall transmitted packets	70,000
Inter-packet transmission interval	20 ms, 100 ms
Transmission power	-10 dBm (outdoors), 0 dBm (indoors)
Packet size	28 Byte

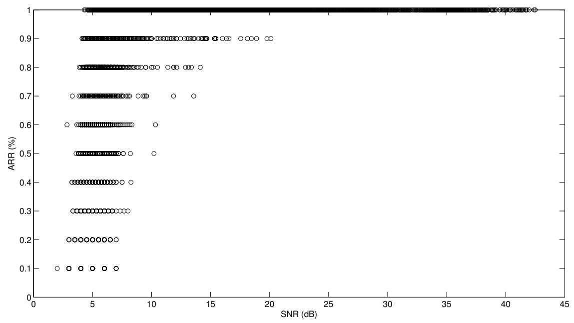


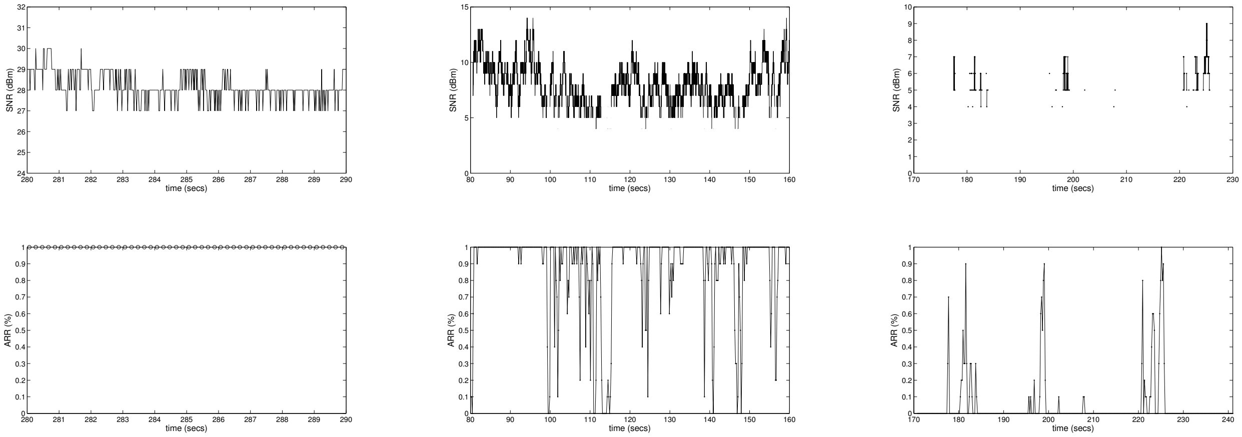
Fig. 1: A summary of the relationship between the SNR and ARR of a wireless link.

We selected ARR for characterizing the quality of a link and signal-to-noise ratio (SNR) for characterizing the quality of received packets. Unlike the RSSI, the SNR contains information pertaining both the received signal's strength and the background noise. Then we evaluated how ARR and SNR are related.

Regardless of the location of the nodes and the distance of separation between them, packets were always received ($ARR \approx 1$) when the SNR was greater than 21 dBm. We characterized this link as a good link, in agreement with previous observations made by other researchers. On the other hand, when the SNR was less than 2 dBm, the ARR was less than 0.1, describing a bad link where 90% of the packets were lost. The region between the good and the bad links describe an intermediate region in which ARR varies uniformly between 0.1 and 0.9. The links in this region are bursty in nature. Our experimental observations are similar to previous findings [18], [1], even though they used differet platforms (TelosB and Micaz). Fig. 1 summarizes the relationship between ARR and SNR for our experiment. Fig. 2 displays the three regions we identified to describe a bad, an intermediate, and a good link and how the SNR and ARR fluctuate in these regions.

IV. LINK QUALITY ESTIMATION

We use the conditional cumulative distribution function (CDF) to describe the duration for which the quality of a link can be considered stable, i.e., all packets transmitted within



(a) Good link

(b) Intermediate link

(c) Bad link

Fig. 2: An illustration of the three link types. In the good link $ARR \approx 1$ all the time. The intermediate link is characterized as $0.1 \leq \text{ARR} \leq 0.9$. In the bad link, $\text{ARR} < 0.1$. $\text{ARR} = 1$ means all packets were received successfully whereas $ARR \approx 0$ means nearly all packets were lost.

this duration most likely experience a similar link quality. If this CDF is available to the MAC protocol or the application, it can determine the number of packets it should transmit successively, how often it should contend to seize the medium, or how long on average it should spend in sleep mode.

A. *Theoretical Conditional CDF*

Suppose the fluctuation of SNR of received ACK packets for a particular link is expressed as a random variable $\mathbf{s}$ with a CDF $F(s) = P\{\mathbf{s} \leq s\}$, where s is a real number. The conditional CDF of the duration in which the link can be considered stable[1] can be expressed as:

$$F\left(\tau|s_{th}\right) = P\left\{\mathbf{T} \leq \tau|\mathbf{s} \geq s_{th}\right\} \tag{3}$$

where, $\mathbf{T}$ is a stable link duration expressed as a random variable, because it cannot be known in a deterministic sense. Equation 3 can also be expressed as,

$$F(\tau|s_{th}) = \frac{P(\mathbf{T} \leq \tau, \mathbf{s} \geq s_{th})}{P(\mathbf{s} \geq s_{th})} \tag{4}$$

$$F(\tau|s_{th}) = \frac{P(\mathbf{s} \geq s_{th}|\mathbf{T} \leq \tau)F(\tau)}{P(\mathbf{s} \geq s_{th})} \tag{5}$$

$$F(\tau|s_{th}) = \frac{P(\mathbf{s} \geq s_{th}|\mathbf{T} \leq \tau)F(\tau)}{1 - F(s_{th})} \tag{6}$$

The expected duration in which the link quality is above the specified threshold can be expressed as:

$$E\left[\mathbf{T}|s_{th}\right] = \int_0^\infty \left[1 - F\left(\tau|s_{th}\right)\right] d\tau \tag{7}$$

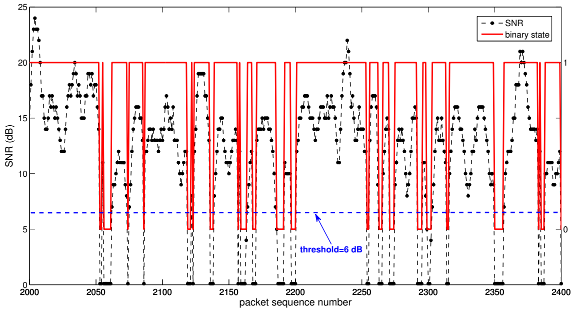


Fig. 3: The fluctuation of SNR in received ACK packets and the transformation of the continuous function to a discrete function to estimate the conditional duration of a stable condition.

The number of packets which should be transmitted in burst can be determined by taking Equation 7 along with the packet size (which is 28 Bytes in a TinyOS environment), the transceiver's data rate (250 Kbps for CC2420), and the MAC protocol primitives (for IEEE 802.15.4 compliant MAC protocols these are CCA, exponential random back-off, and SIFS) into consideration.

B. *Empirical Conditional CDF*

Equation 7 can be determined empirically for each link within a network. We shall demonstrate this approach by example. The CC2420 transceiver can decode a packet correctly only when the packet error rate (PER) is less than one percent. According to the IEEE 802.15.4 specification, a typical low-cost detector implementation is expected to meet the 1% PER requirement for SNR values of 5-6 dB [19]. Therefore, we choose 6 dB as our first threshold. However, because most real

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[1] It should be noted that stable does not imply good. It simply mean that the quality of the link in this duration can be considered unchanging.

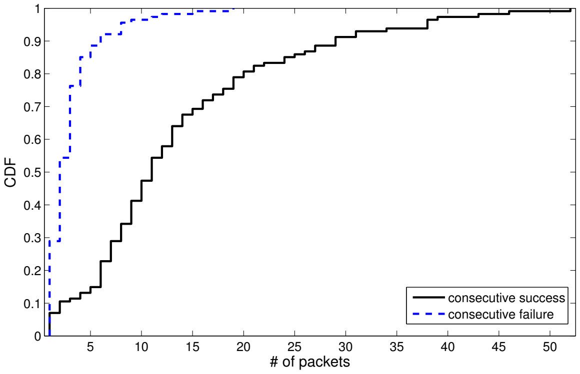


Fig. 4: The empirical conditional distribution function of consecutive success and failure of a link.

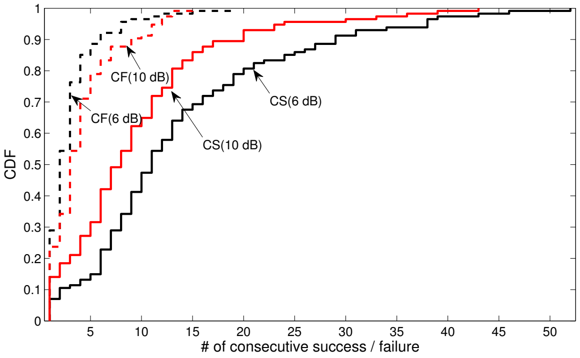


Fig. 5: Empirical conditional CDF of consecutive success (CS) and failure (CF) for different SNR thresholds.

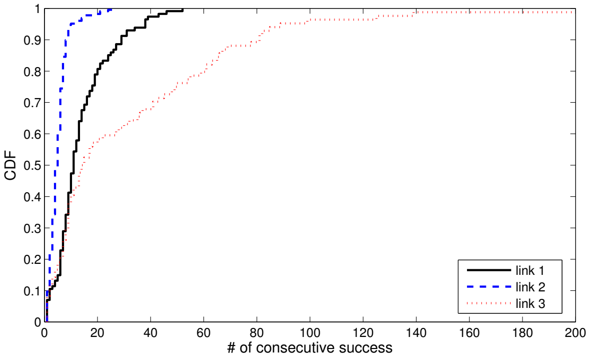


Fig. 6: The conditional CDF of consecutive success for different links.

world links are in the intermediate region, we also considered a threshold of $SNR > 10\ dB$.

Fig. 3 displays a snapshot of the fluctuation of the SNR of acknowledgment packets during the continuous transmission of 30,000 packets in an outdoor location. The distance between the two communicating nodes was 5 m and the transmission power of both nodes was -10 dBm. In order to determine the durations in which the link quality stays above 6 dB continuously, we transformed the continuous function to a discrete function by setting 6 dB as the threshold:

$$f(t) = \begin{cases} 1 & \text{if SNR} \geq 6\ dB \\ 0 & \text{otherwise} \end{cases} \tag{8}$$

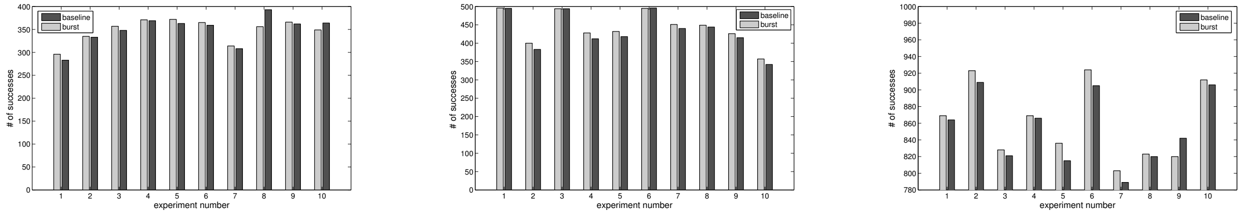
The discrete function can be understood as a function of time since the packets are transmitted consecutively and the width of each pulse in the function can be understood as the time duration in which the channel behavior can be considered as stable because all the packets transmitted within this duration are either received or lost with the same probability. By measuring the width of each pulse which are above the threshold, the conditional distribution function of the time duration for successfully transmitting packets in succession (in other words Equation 6) can be obtained. Conversely, the conditional CDF of the duration in which successive packets fail can be obtained by measuring the width of each pulse below the threshold.

Fig. 4 displays the conditional CDFs of continuous success and continuous failure of the link described above. The SNR threshold was 6 dB. Fig. 5 shows how the conditional CDF of continuous success changes for different SNR thresholds. In general, as the SNR threshold increases, the probability of receiving packets successfully increases, but the probability of getting a stable link decreases. Fig. 6 compares the conditional CDF of continuous success for different links with the same SNR threshold.

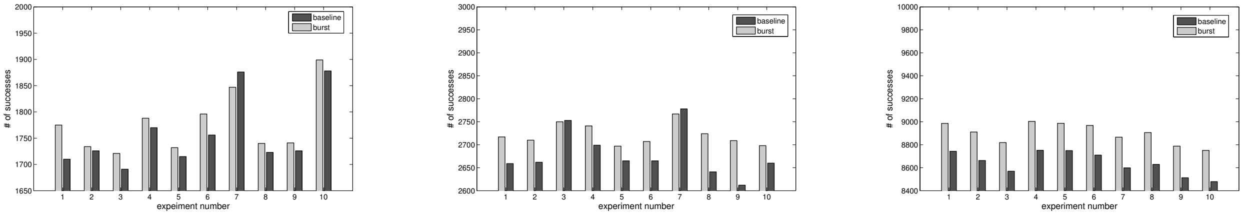
V. EVALUATION

To evaluate the usefulness of Equation 7, we first transmitted 30,000 packets continuously in each link in order to obtain statistics pertaining to the SNR fluctuation of received ACK packets. There was a 20 ms interval between transmissions to annotate the received packets and to store the metrics we needed to characterize the packets (RSSI, LQI, and SNR). After the transmission was completed, we obtained the empirical CDF of the durations for continuous success (CS) and continuous failure (CF). We fixed the SNR threshold at 6 dB.

During the test phase, we transmitted 400, 500, 1000, 2000, 3000, and 10000 packets, but this time the packets were transmitted with and without intermission. For the case of with intermission, we used the expected duration of continuous success to transmit the packets in burst and the expected duration of continuous failure to make the nodes refrain from transmitting. In all the experiments, lost packets were not retransmitted. For each test case, we repeated the experiment



(a) 400 packets (b) 500 packets (c) 1000 packets



(d) 2000 packets (e) 3000 packets (f) 10000 packets

Fig. 7: Comparison of the successfully transmitted packets when they were transmitted continuously without intermission and then they were transmitted by taking the expected durations of continuous success and continuous failure in to account.

TABLE II: A summary of the parameters used to transmit packets in burst in different links for $SNR = 6\ dB$ as a threshold).

	link1	link2	link3	link4	link5
CS	29	2	2	8	6
CF	12	13	6	7	3
location	9 m	27 m	35 m	13 m	3 m
power	0 dBm	0 dBm	0 dBm	-3 dBm	-10 dBm

ten times. Fig. 7 compares the number of successfully transmitted packets when packet transmission was made without intermission and when packet transmission was made with the knowledge of the conditional CDF of CS and CF. As can be seen in the Fig. 7, our approach yields (90% of the time) the highest number of successfully transmitted packets for most of the test cases. This is particularly the case as the number of transmitted packets increased. When the number of transmitted packets increased, so did the transmission time, in which case the link characteristic was better represented by the statistics we obtained by transmitting the 30,000 packets.

Figure 8 compares the average number of successfully transmitted packets for five different indoor and outdoor links. This time we transmitted 1000 packets for testing. Table II summarizes the parameters we computed or fixed for the experiment.

VI. CONCLUSION

In this paper we investigated fluctuations of link quality in wireless sensor networks and proposed a model to estimate the expected duration of stable transmission periods. We employed conditional distribution functions in our model where the link quality duration was conditioned by the signal-to-noise ratio thresholds of acknowledgment packets. We used the model to determine the number of packets that can be successfully transmitted in burst. In other words, nodes transmit packets in burst when the link quality is good but they refrain from transmitting packets when it is bad. Our model enables them to determine for how long on average the quality of a link remains good and for how long it remains bad. We deployed IMote2 nodes in various places and considered different separation distances and transmission power levels to obtain statistics pertaining to link quality.

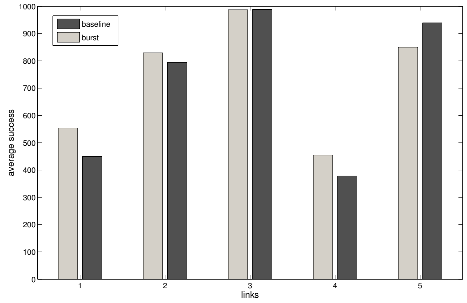


Fig. 8: Comparison of the successfully transmitted packets in burst in different indoor and outdoor links.

The experiment results confirm the plausibility of our approach. We compared our approach with a transmission scheme that transmitted packets in succession without taking link quality fluctuations into account. Altogether we transmitted 70,000 packets to obtain statistics and 16,900 packets to evaluate the performance of our approach. 90% of the time, our approach outperformed in transmitting packets successfully.

In future, we shall continue improving the model, so that it can dynamically update the statistics pertaining to link quality fluctuations. One aspect we shall consider is using Bayesian Estimation Techniques [2] to update the conditional distribution function.

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