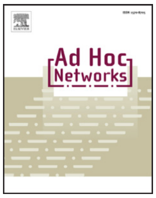
Ad Hoc Networks 000 (2017) 1–18

Contents lists available at ScienceDirect

Ad Hoc Networks

journal homepage: www.elsevier.com/locate/adhoc



Real-time link quality estimation for industrial wireless sensor networks using dedicated nodes

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ARTICLE INFO

Article history:
Received 24 August 2016
Revised 24 February 2017
Accepted 27 February 2017
Available online xxx

Keywords:
Industrial wireless sensor networks
Link quality estimation
Adaptive protocols

ABSTRACT

Adaptive mechanisms, such as dynamic channel allocation or adaptive routing, are used to deal with the variations in the link quality of Wireless Sensor Networks (WSN). In both cases, the first step is to estimate the link quality, so that the network nodes can decide if a channel or route change is needed. This paper proposes a Link Quality Estimator (LQE) for Industrial WSN, and a new type of node, the LQE node, that estimates the link quality in real-time, using the Received Signal Strength Indication (RSSI), and information obtained from received data packets. The proposed LQE is capable of capturing the effects of multipath, interference, and link asymmetry. Experiments were performed in a real industrial environment using IEEE 802.15.4 radios, and models were developed to allow the use of RSSI samples to proper estimate the link quality. A comparison was performed with a state-of-the-art LQE, the Opt-FLQE, and the results showed that the proposed estimator is more accurate and reactive for the type of environment in study. Different from other LQEs in literature, in the proposed LQE the sensor nodes do not need to send broadcast probe packets. Besides, using the LQE node, the other nodes of the WSN do not need to stop their operation to monitor the link quality.

1. Introduction

The use of Wireless Sensor Networks (WSN) to implement monitoring and control systems in industrial environments has some advantages when compared with the use of wired networks, such as low cost and high flexibility. Some applications were proposed in literature, such as motor monitoring [1], temperature monitoring [2], and aperiodic wireless control systems [3]. However, it is necessary to deal with typical problems of wireless networks, such as electromagnetic interference [1], and high attenuation, due to the presence of many objects and obstructions [4]. Many industrial environments also present characteristics that make the wireless channel non-stationary, for long time periods, which can cause abrupt changes in the characteristics of the channel over time [5].

It is possible to deal with these problems using mechanisms that allow the network to self-adapt to the variations that occur in the link quality over time, such as adaptive routing [6] or Dynamic Channel Allocation (DCA) [7], in which the WSN nodes change the route or the channel when the quality decreases. The IEEE 802.15.4 standard, which is the usual communication standard for WSN, defines sixteen channels in the 2.4 GHz band, and the characteristics of the communication medium can be different for different channels [8]. Even for standardized devices, that use channel hopping, such as the WirelessHART and ISA100 [9], the use of DCA mechanisms can be advantageous to properly configure the blacklist, in order to dynamically modify the channels that are considered in the channel hopping mechanism. To implement these adaptive protocols, a Link Quality Estimator (LQE) is necessary to provide information about the quality of the links to the network nodes.

This paper proposes a novel LQE and a new architecture for industrial WSN. The use of dedicated nodes (the LQE nodes) to monitor the link quality in industrial WSN is considered. Using the LQE node, the Received Signal Strength Indication (RSSI) can be used in a more effective way, since raw values of RSSI are not enough to properly estimate the quality of the wireless channel, but with

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http://dx.doi.org/10.1016/j.adhoc.2017.02.007
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Please cite this article as: R.D. Gomes et al., Real-time link quality estimation for industrial wireless sensor networks using dedicated nodes, Ad Hoc Networks (2017), http://dx.doi.org/10.1016/j.adhoc.2017.02.007

a more detailed analysis of several values of RSSI it is possible to identify the problems that affect the channel quality.

Two main challenges are addressed in this paper. The first one is the development of metrics to capture all the aspects of the channel that affect the link quality and its dynamics, such as fading, shadowing, interference, and link asymmetry. It is necessary to find a good trade-off between the stability and reactivity, to estimate the link quality accurately, even with the small and rapid variations in the channel quality due to the multipath fading. On the other hand, it is necessary to rapidly identify abrupt and persistent changes in the link quality.

The second one is the design and implementation of a LQE that allows to monitor, in real-time, the quality of various links, without causing overhead on the sensor nodes, or on the network, especially on the end nodes, which present additional resource constraints. Thus, the models developed to implement the proposed LQE use only information obtained at the receiver side, and no extra traffic is generated in the network. Besides, the LQE must have low computational complexity in order to run on low-cost microcontrollers. Even considering these restrictions, the LQE must be capable of evaluating the quality of the link, in both directions, and identify interference problems.

Different from other LQEs [10–14], the proposed LQE does not generate extra traffic through the use of probe packets or redundancy in the data packets, neither performs processing on the transmitter. This approach allows real-time estimation using the LQE node, which can process many values of RSSI, and information obtained from received data packets, while the other nodes of the WSN remain operating normally, which incurs in a low overhead. A comparison was made with the Opt-FLQE [13] estimator, which is a LQE based on fuzzy logic. The results showed that the proposed estimator is more accurate and reactive for the type of environment in study.

The main contributions of this paper are:

- The realization of a comprehensive set of experiments in a real industrial environment using IEEE 802.15.4 radios to obtain insights on the implementation of the LQE node;
- The development of models to estimate the link quality in both directions and the influence of interference, using samples of RSSI and information obtained from received data packets;
- The design and implementation of a new type of node, the LQE node, and a novel LQE, to estimate the link quality in real-time;
- The validation of the proposed estimator through experiments in a real industrial environment.

2. Background information

2.1. The wireless channel in industrial environments

The industrial environment usually contains metallic and mobile objects, such as robots, cars and people. This influences both the large-scale and small-scale fading. The power of the received signals depends on the transmission power, the antennas gains, the distance between transmitter and receiver and the effects caused by the environment. Even with the same values for the aforementioned parameters, there is a variation in the mean received power, depending on the place where the measurement is performed, which is known as log-normal shadowing. The log-normal shadowing model has been used to model the large-scale path loss and shadowing in industrial environments [4].

Besides path loss and shadowing, it is also necessary to analyze the small-scale channel fading due to rapid changes in the multipath profile of the environment, which is caused by the movement of objects around the receiver and transmitter. Experiments demonstrated that, in industrial environments, the temporal attenuation follows a Rice distribution. In industrial environments the K factor of the Rice distribution has a high value. For the experiments described in [4], in industrial environments, K presented values between 4 dB and 19 dB, while in office environments, values between −12 dB and −6 dB were reported, as discussed in [4]. This can be explained by the open nature of industrial buildings and the large amount of reflective materials. Thus, there are many time-invariant rays and only a small part of the multipath profile is affected by moving objects.

A study on the properties of the error in bit and symbol-level, in industrial environments, was described in [15]. For environments with multipath fading, the bit errors are uniformly distributed inside the corrupted packets, and the channel memory is only four bits long. The use of forward error correction was proposed. However, most of packets in the experiments were lost in air, in scenarios with multipath fading. Thus, to achieve good quality, it is also necessary to pick channels or routes that suffer less with the multipath fading.

The wireless channel can be modeled as wide-sense stationary for a short period of time. However, the channel's properties can change significantly in a period of a few hours, due to changes in the topology of the environment. This changes are not taken into account by the usual fading distributions [16].

A characterization of the wireless channel in an industry was performed for a long time period (20 h) in [17]. The results showed that the Rice distribution only fits the received power for small periods of time, in which the mean value of the received power remains constant. However, abrupt changes in the channel characteristics can occur when the channel is analyzed for a long term, and differences on the mean value of the received power are observed, although the transmitter and receiver remain static. For example, in the experiment described in [17], the received power varied around −55 dBm during 7 h, and after this period the mean value of the received power changed abruptly to −46 dBm. An experiment described in [18] also presented similar behavior.

A composite distribution has been described to capture both shadowing, and fading for the long term. The model is called Nakagami-m/Log-normal. The parameter of the Nakagami-m distribution defines the level of fading, and the parameters of the log-normal distribution define the effects of shadowing [5].

2.1.1. Power delay profile and coherence bandwidth

Some papers have described experiments to identify the Root-Mean-Square (RMS) delay spread in industrial environments [19,20]. The RMS delay spread gives an indication of the level of multipath encountered during the signal transmission, and is calculated from the power delay profile of a measured signal [20].

Reflective industrial environments present many multipath components, which lead to a high value of RMS delay spread. For example, in the experiments described in [19], in the 2.4 GHz band, the RMS delay spread was 294.19 ns. As the radios used in WSN have relatively low symbol rate, the inter-symbol interference may not be a problem for WSN in indoor environments.

The coherence bandwidth is the frequency interval (Δf) in which the frequency components are correlated, and can be defined according to $\Delta f \approx 1/\alpha\tau_{RMS}$, in which τ_{RMS} is the RMS delay spread in seconds, and α is a factor that can vary according to the shape of the power delay profile [21]. Considering $\tau_{RMS} = 294.19$ ns for an industrial environment [19], and considering $\alpha = 5$ (correlation between frequencies larger than 90%), $\Delta f \approx 10^9/(5 \times 294.19) \approx 680$ kHz.

The IEEE 802.15.4 standard defines sixteen channels in the 2.4 GHz band, with 2 MHz of bandwidth, and channel spacing of 5 MHz. Thus, the channels are highly uncorrelated. Experiments described in [22] have found that changing the communication channel can lead up to 30 dB difference in the received power, in

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