

Performance Tracking and Risk Assessment of Wireless Mesh Networks: A WiP Framework

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Abstract—Wireless mesh networks have, in recent years, gained a strong foothold in the industry with a steady growing number of installations. Although wireless solutions are now "proven in use", some of the challenges e.g. QoS which arise from this accelerated adoption have not fully been addressed. In this paper, a framework for tracking QoS and assessing the risk to performance of wireless mesh networks is proposed. This paper presents and consolidates a list of performance indicators which are relevant to industrial applications. Based on those indicators, a method to visualize them in a single graph with a unified scale is introduced. This QoS based application profiling approach keeps track of overall network performance and relevant trade-offs. Moreover, this paper proposes a method to assess the risk to network performance and eventually to QoS by using historical statistical data.

Keywords— WMN; WSN; reliability; uptime; stability; RSSI; IEEE802.15.4; Wi-Fi; KPI; tracking; forecast; SNR; VaR; QoS

I. INTRODUCTION

Industrial wireless technology has passed the infancy stages and can be seen to be actively utilized within industrial applications. Wireless mesh networking has been a key enabler behind the proliferation of wireless instrumentation in the industry and WirelessHART, ISA100.11a and ZigBee are a few such examples. In this research, the scope of wireless mesh networks is limited to Wireless Sensor Networks (WSNs). Today, WSNs are pervasive in monitoring applications, however, for control and safety applications they are relatively new. In these applications, the Quality of Service (QoS) is of utmost importance. However, the QoS requirements varies from application to application. Moreover, the need for network convergence is ever higher, as the end users expect to run multiple different applications on the same infrastructure. This paper does not deal with QoS concepts or methods, rather it focuses on parameters which are important to quantify performance.

Due to the inherent limitations of wireless networks, there is a need to identify, track and measure network performance. It is important to both the network designers and operators to ensure that the target application will be guaranteed QoS at the time of design and commissioning, and that it continues to do so throughout the operational lifetime. This research is an effort towards addressing some of these challenges by defining a framework of terminologies and methods to answer the following questions:

- Q1) Which performance indicators are important to quantify the behavior of a wireless sensor network?
- Q2) How to simply visualize wireless network performance?
- Q3) How to quantify the risk to network performance?

These questions have to be considered in the wider framework of tools envisioned to be developed to track and assess the expected behavior of industrial WSNs. This WiP paper only touches on a few aspects linked to these questions.

In [1] the authors investigate how the WSNs perform in the case when the sink node moves via two simulation results using the AODV protocol. An analytical performance model of IEEE 802.15.4 network in which the sensors are at the tips of a star topology is presented in [2]. The authors further show how the saturation analysis can be used to obtain an analytical model for the finite arrival rate case. [3] shows the Markov decision process framework and its applications in WSNs. This decision-making tool assists in developing adaptive algorithms and protocols. Markov chains are often used to determine system performance and in [4] it is shown how model specification and analysis techniques from concurrency theory can be applied to performance evaluation. [5] provides a new definition to measure and implement QoS in low duty cycle WSNs. This paper builds on the concepts introduced in relevant literature.

The layout of the rest of this paper is as follows: Section II presents an overview of the terms and definitions related to performance metrics of networks and systems. This section also introduces new terms which are important to identify application QoS profile. Section III demonstrates the practicality of using these indicators through an experimental setup. Furthermore, Section IV proposes a method to evaluate risk related to network and application performance. It is followed by conclusion in Section V.

II. PERFORMANCE INDICATORS AND QUALITY OF SERVICE

A. Performance Indicators

The performance indicators for industrial wireless sensor networks can be divided into three categories.

1) Application Performance Indicators

These performance indicators have a direct impact on the Quality of Performance (QoP) of the target application. Therefore, it is vital to monitor these parameters to ensure adequate QoS is maintained.

- Data Latency (D_L): It is a measure of how long it takes a packet originating from a sensor node to reach its destination. In this paper, it is limited to upstream data latency, D_L , and for satisfactory application performance it has to meet the following criteria:

$$D_L < \text{periodic update interval of sensor}$$

To represent data latency on a scale from 0 to 100%, a term referred to as Latency Margin Ratio (LMR) is defined, and is as follows:

$$LMR = \frac{(\text{periodic update interval of sensor} - D_L)}{\text{periodic update interval of sensor}} \times 100 \quad (1)$$

- Data Generation Rate (DG_R): It is a measure of number of data packets generated by a node in a unit interval of time. In control and safety applications, data packets are generated periodically. It follows this condition:

$$DG_R \leq \text{maximum data throughput supported by the protocol}$$

- Reliability [6]: It is the probability to transfer a unique data packet through the network within certain latency. This definition is in-line with its general use in networking domain. In addition, the term Packet Reception Ratio (PRR) and Packet Delivery Ratio (PDR) are also often used synonymously. In reliability, acknowledgments are not considered. Furthermore, Packet Lost Rate can be derived from reliability. Here, reliability is defined as follows:

$$\text{Reliability} = \left(\frac{\text{unique packets received}}{\text{total transmitted packets}} \right) \times 100 \quad (2)$$

Data packet received after *periodic update interval of sensor* duration has passed is considered as data lost. In contrast, from a system's viewpoint reliability refers to the probability that an item will perform a required function, under stated conditions, for a period of time.

- Availability [7]: It can be defined as the proportion of time for which the equipment is able to perform its function. Therefore, it takes repair time in consideration. From WSN view-point it is often considered as the fraction of times that the sensor was able to transmit its packet through the network when it wanted. Primary difference between reliability and availability is that in former case it is over a time interval and in latter it is instant of time.
- Data Outage (D_O): It is referred to as unavailability of network resources for a continuous duration of time. As a result, continuous data packets are lost.

In safety applications, a continuous loss of packets can lead to automatic triggering of fail-safe operation; therefore, it is highly undesirable.

To calculate this trigger margin a term *Data Outage Margin (DOM)* is defined in Eq 3.

$$DOM = \left(\frac{\text{outage trigger duration} - D_O}{\text{outage trigger duration}} \right) \times 100 \quad (3)$$

Here, *outage trigger duration* refers to a minimum outage (aka blackout) time which will trigger a safety action.

2) Operational Performance Indicators

These performance indicators capture the operational conditions of the installed wireless network.

- Operational Temperature: It is the average operational temperature of wireless nodes in the network. Here, it is represented as a percentage of operational bounds.

Operational Temperature Margin (*OTM*) for each node is represented by Eq 4.

$$OTM_{\text{node}}(T) = \left\{ \begin{array}{ll} \left(\frac{T_{\max} - T}{\Delta T} \right) \times 100 & T \geq T_{\text{avg}} \\ \left| \left(\frac{T_{\min} - T}{\Delta T} \right) \right| \times 100 & T < T_{\text{avg}} \end{array} \right\} \quad (4)$$

$$\Delta T = (T_{\max} - T_{\min}) / 2$$

$$T_{\text{avg}} = T_{\min} + \Delta T$$

OTM of the total network is represented by OTM_{Σ} , and is the average of all nodes collective *OTM*.

- Network Utilization: It is the ratio of current network usage to maximum network capacity that it can handle.

3) Network Performance Indicators

These performance indicators represent the performance and efficiency of the installed wireless sensor network. In addition, these indicators can be used to compare the performance of different protocols.

- Network Stability [6]: It represents the ratio of successful packet transmissions, i.e., acknowledged packets to the total number of packet transmissions.
- Average Network Depth: It is the average number of hops a packet has to travel to reach its destination.
- Serviceability: It determines how long each network outage takes to fix. It takes into consideration factors such as device failure and network switch over time.
- RSSI: Received Signal Strength Indicator is the RF power input to the receiver.
- Mesh Strength Indicator (MSI): A mesh network utilizes the availability of multiple communication nodes in the network to relay data over the network. As a result, a full mesh network is able to overcome some issues related to wireless media and are adaptable and expandable. However, it requires a network evaluation to quantify whether a network is a strong mesh or a weak mesh. Here, this evaluation is referred to as MSI.

MSI of a node (*i*) can be represented as follows:

$$MSI(i) = \left\{ \begin{array}{ll} 0\%, & \text{Node } (i)_{\text{Diversity}} \leq 1 \\ 25\%, & 1 < \text{Node } (i)_{\text{Diversity}} \leq 2 \\ 50\%, & 2 < \text{Node } (i)_{\text{Diversity}} \leq 3 \\ 75\%, & 3 < \text{Node } (i)_{\text{Diversity}} \leq 4 \\ 100\%, & \text{Node } (i)_{\text{Diversity}} \geq 5 \end{array} \right\} \quad (5)$$

$$\text{Node } (i)_{\text{Diversity}} = \sum_{j=1}^N LQ_{ij}$$

Here, LQ_{ij} represents the Link Quality (*LQ*) between

node i and neighbor j . It is also assumed that link between these nodes is reciprocal. If $j \neq i$, LQ_{ij} is:

$$LQ_{ij} = \begin{cases} 1, & RSSI_{ij} \geq RSSI_{min} \\ 0, & RSSI_{ij} < RSSI_{min} \end{cases}$$

If $j = i$, then $LQ_{ij} = 0$.

$RSSI_{min}$ is equal to receiver sensitivity plus fade margin.

MSI of the network of N nodes is represented as:

$$MSI_{\Sigma} = \{MSI(1), MSI(2), \dots, MSI(N)\}$$

The ranking of complete network is as follows:

$$MSI_{Rank} = \text{Min}(MSI_{\Sigma})$$

- **Medium Utilization [8]:** The Medium Utilization (MU) factor is a measure to quantify the amount of resources (Power and Time) used by non-adaptive equipment. MU is defined in EN 300 328 standard.

$$MU = \left(\frac{P}{100}\right) \times \text{Duty cycle} \quad (6)$$

Where P is the output power in mW .

Duty cycle is defined in the EN 300 328 standard.

A term relevant in this context is, *Medium Utilization Margin (MUM)*, and is derived from MU formula. Here *Duty cycle* is presented in percentage.

$$MUM = \left(\frac{P}{100}\right) \times (100 - \text{Duty cycle}) \quad (7)$$

- **Spectrum Efficiency (S_E):** It is the ratio of network throughput to the communication system bandwidth.

B. Quality of Service

The term *service* in networking refers to the capability to exchange information through a telecommunications medium [9]. Moreover, the word *quality* is used to imply whether the service satisfies the user's expectation or not. In short, QoS is used to capture user's perception of the service. If QoS is within application's tolerance bounds then the performance of the application is acceptable. Therefore, a network has to configure or tune its connection parameters to achieve a particular QoS.

Fig.1 represents a chart which shows the vital parameters which need to be tracked in order to monitor the performance of a WSN and its target application. Additional parameters which are presented in this section but not included in this chart are currently omitted. The target application which is used in this paper have minimum service constraints and are shown in Fig.1 as acceptable and unacceptable QoS profiles.

III. EXPERIMENTAL SETUPS AND RESULTS

The experimental setups used in this paper comprise of two configurations. They both use wireless sensor nodes which communicate using IEEE802.15.4 PHY and TDMA based MAC. **SETUP1:** This setup comprises of 10 wireless sensor nodes and 1 wireless sensor network coordinator (*aka* sink node). These nodes were all within one-hop of the coordinator. These nodes were all installed on static platform and they formed a star-mesh

network. The nodes were programmed to communicate periodically with the coordinator. This experiment was repeated four times and the outcome of this experiment is shown in Fig.2. During all these four durations of operation QoS delivered by the wireless network was adequate. During Duration 4 of the operation, the network stability went down, which resulted in increase in medium utilization and also in decrease of data outage margin due to data loss and packet retransmissions.

SETUP2: This setup comprises of 9 wireless sensor nodes and 1 wireless sensor network coordinator. The network is based on mesh connectivity with up to 3-hops depth to the coordinator. 3 nodes were installed on a movable platform and the other 6 on fixed platform. The nodes were programmed as in SETUP1.

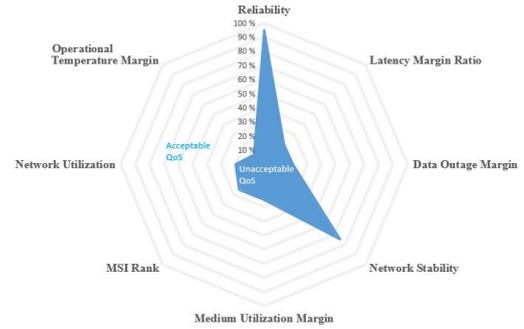


Fig. 1. Performance indicators of a wireless sensor network.

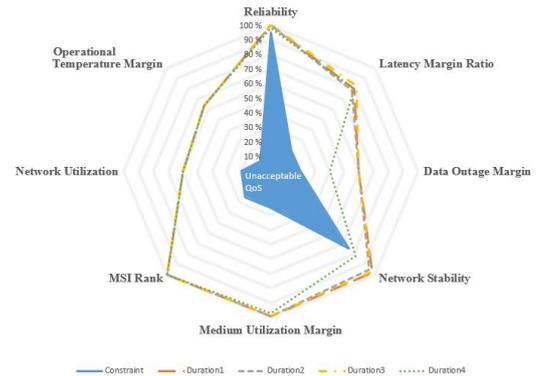


Fig. 2. Performance indication of setup1 test outcome.

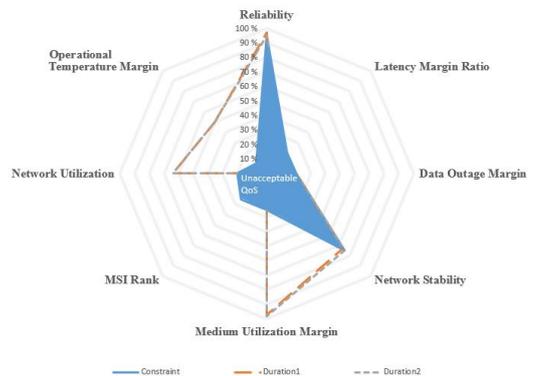


Fig. 3. Performance indication of setup2 test outcome.

This experiment was conducted two times. In this case, it was found that both the MSI_{Rank} and stability of the network was inadequate and therefore the application performance indicators (reliability, latency and data outage margin) were compromised.

IV. PERFORMANCE RISK ASSESSMENT USING HISTORICAL STATISTICAL DATA

A method which is widely used in the financial industry to calculate market risk on a holding position of a portfolio of financial assets is Value at Risk (VaR) [10]. The basic principles of this statistical technique can also be applied to wireless networks in order to measure and quantify the level of risk within a specific network (which consists of wireless instruments) over a specific time frame. By measuring the risk; which in this case are related to the network KPIs like latency and reliability the network operators can measure and control the level of risk which the wireless network can undertake without sacrificing the performance.

The VaR is presented in three variables [10]: the amount of potential loss, the probability of that loss and the associated time frame. To estimate VaR, either a parametric or non-parametric techniques can be adopted. Delta-normal method and Monte Carlo simulation are examples of parametric techniques; whereas, historical simulations is non-parametric method. The latter option is currently the main focus of this research. The key assumption in this simulation is that the ‘history repeats itself’, i.e. possible future scenarios are fully represented by what happened over a specific historical window.

To estimate Performance at Risk (PaR), the same principals as used in a typical VaR are applied. In this scenario, the following setup and assumptions are used:

- A wireless network is operated for a sufficient period of time and the collected performance indicators are adequate to capture the network behavior. Here, the SETUP1 is used, and the data collected over a period of 1 week is assumed to be sufficient.
- The fact that most of wireless instruments in the industry are installed on fixed-assets, this assumption is justifiable and can in most normal conditions provide an adequate characterization of RF media behavior. Even if the platform is mobile, it follows a fixed trajectory.
- Performance indicators are calculated using average values of the collected data packets. In this case, average is calculated for every one hour of operation.
- Performance indicators for each one-hour data are calculated and the change in each performance indicator from one-hour to the other hour are calculated. This series of data is used to estimate the expected PaR in the next operation interval of time.
- The expected performance of the WSN for the next one-hour of operation with the 95% of confidence interval is presented in Fig.4. The performance indicators showed here take into consideration the potential performance loss.

In short, it is expected that the operation of the network in next one-hour will be adequate.

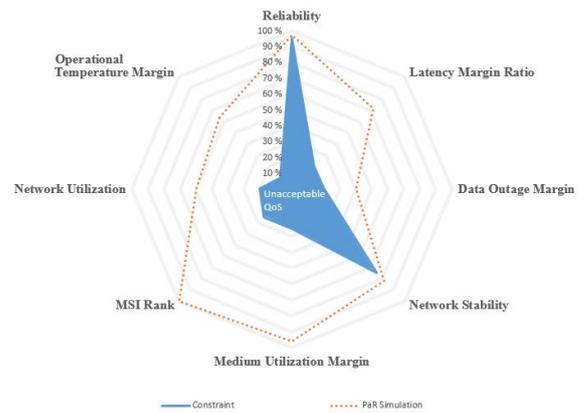


Fig. 4. Expected network performance with PaR adjustment.

V. CONCLUSION

In this paper, a framework for tracking and predicting the performance of industrial wireless sensor networks has been proposed in Section II. Given the fixed and static nature of wireless instruments in industrial plants, it is reasonable to assume that the network performance forecast can be made using historical statistical data, a method which is widely used in the finance industry.

The results from an empirical study presented in Section III found that a network with a high MSI rank was able to perform adequately with desired reliability and latency. The proposed visualization method also highlighted the fact that a strong mesh can improve reliability; however, due to practical reasons, there is a limit to network capacity which can be handled by the sink node and the network manager. Therefore, it is not always feasible to increase a mesh network strength when the network is operating at near limits of the capacity. The network performance indicators capture these limits.

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