Fault Detection in WSNs - An Energy Efficiency Perspective Towards Human-Centric WSNs

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Abstract Energy efficiency is a key factor to prolong the lifetime of wireless sensor networks (WSNs). This is particularly true in the design of *human-centric wireless sensor networks* (HCWSN) where sensors are more and more embedded and they have to work in resource-constraint settings. Resource limitation has a significant impact on the design of a WSN and the adopted fault detection method. This paper investigates a number of fault detection approaches and proposes a fault detection framework based on an energy efficiency perspective. The analysis and design guidelines given in this paper aims at representing a first step towards the design of energy-efficient detection approaches in resource-constraint WSN, like HCWSNs.

1 Introduction

Energy efficiency represents a key research issue in resource-constraint wireless sensor networks (WSNs). In particular, energy efficiency is a crucial aspect of the emerging concept of *Human-Centric WSNs (HCWSNs)*, where sensor nodes are more and more embedded in the environment and even in the human body. These *human-based sensors* must be able to communicate with each other in a resource-constraint, open and dynamic setting. Resource limitations in this kind of networks make fault detection greatly different from traditional, static WSNs. As a result, energy efficiency (which is mainly related to the amount of communication exchanges) becomes a key design aspect to build robust HCWSNs.

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G. Jezic et al. (eds.), *Agent and Multi-Agent Systems: Technologies and Applications*, Smart Innovation, Systems and Technologies 38,
DOI 10.1007/978-3-319-19728-9_24

While current literature discusses detection approaches in different ways, it is hard to find one explicitly discussing the position of message exchanging during the process of fault detection, and how this message exchanging impacts the energy efficiency of a fault detection approach. Yu et al. [39] investigate the three-phase fault management process, i.e., fault detection, diagnosis and recovery. They discuss explicit and implicit detection, centralized and distributed approaches, neighbour coordination, clustering and distributed detection techniques. Paradis and Han [30] also give a survey to fault management in WSNs. They describe fault prevention, detection, isolation, identification, and recovery techniques separately. Mahapatro and Khilar [22] adopt a fault type model from [1] and provide their own taxonomy of fault detection techniques. They discuss both centralized and distributed fault diagnosis approaches. Particularly, they classify distributed approaches into several categories, including Hierarchical Detection, Node Self-Detection, and Clustering-Based Approaches from architectural viewpoint; Test-Based Approaches, Neighbor Coordination Approaches, Soft-Computing Approaches, Watchdog Approaches, and Probabilistic Approaches with their focuses on how to make decision; and also Diagnosis in Event Detection Domain. What is worth mentioning is that the neighbor coordination in [22] concerns majority voting and wighted majority voting, instead of focusing only on coordination between neighbors discussed in [39]. Jurdak et al. [10] present a model including different types of WSN anomalies. They illustrate a set of anomaly detection strategies and divide them according to centralized, distributed and hybrid architectures. They also provide some design guidelines for anomaly detection strategies. Rodrigues et al. [32] evaluate fault diagnosis tools in WSNs in a comparative way. The comparison framework consists of architectural, functional, and dynamic aspects as different dimensions.

Contribution of the Paper. This paper extends current literature by adding a perspective on energy efficiency, as this represents a key aspect to design and build the emerging concept of HCWSNs. In the rest of the paper, we first illustrates our fault detection framework (Sect. 2). Then, in Sect. 3, we present and use a set of evaluation criteria to compare fault detection approaches, with emphasis on energy efficiency. In Sect. 4 we sum up some guidelines for energy-efficient fault detection. Sect. 5 concludes the paper.

2 Fault Detection Framework

The process of fault detection is mainly about making a judgement based on related information. Most of the information is collected within the whole or part of the WSN by message exchanging, which has great impacts on energy efficiency. Here we identify *information collection* and *decision making* as two major components of fault detection framework and describe several design considerations of these two components in the following.

2.1 Information Collection

We focus on three characteristics that can have an impact on message exchanging, namely *Message Exchange Pattern*, *Message Design*, and *Communication Range*. Table 1 lists these characteristics and possible options.

Table 1 Design considerations of information collection

Characteristics		Options	
Message exchange pattern		Active probing	Passive observing
Message desing	Content	Status indication	Sensor readings
	Size	Binary bit	User defined
Communication range		Global	Local

Message Exchange Pattern (MEP) is the way the nodes exchange messages inside the network. Two typical patterns may be used during message exchanging, two-way request-reply and one-way broadcasting. The first one uses pair-wise query-based messages, mostly in hierarchical topologies. In this paper we call it *Active-Probing (AP)*. The second one is called *Passive-Observing (PO)*, which is more common on flat topologies, with messages sent without requested.

Message Design (MD) mainly concerns about the content and the size of the message during the information collection step. The content of the message may be an environmental measurement such as the temperature or a network metric. The content of message is greatly related to the type of fault that the fault detection approach is looking for. For instance, if we have be a periodic "IAmAlive" message, indicating the health status of the node, most probably the fault detection approach is dealing with functional faults. The size of the message is also an attribute that can affect the performance and the energy efficiency. To this end, it is very important to have a tradeoff between the message size and comprehensive meaning.

Communication Range (CR) can be defined by how many sensors are involved during the information collection step. In centralized fault detection most of the times the messages are exchanged among the central node and the nodes in the network. For the case of distributed fault detection approaches the CR may include the one hop neighbours or a set of nodes in a cluster or only one sensor.

2.2 Decision Making

In order to decide whether there is a fault or not, sensor nodes need an input that can be obtained from the exchanged messages. The context information is always application-depended and it is hard to have comprehensive view. We describe the characteristics of the context information as a list of *Assumptions*. The *Calculation Method* and the *Output Range* of calculation are the other critical parts of the decision making phase.

Assumptions (ASMPs). The characteristics of the context of a fault detection approach might have several dimensions. Some of them may be too application-specific to describe. We focus on those which are general enough and organize them according to the components of fault detection in WSN. Except functional, informational and communicational components of WSNs, faults themselves are another fundamental component in fault detection. In Table 2 we illustrate a summary with an indicating name *ASMP_X_i*: *ASMP* stands for the assumption, *X* stands for the component category, it can be *FU* for functional, *IN* for informational, *CO* for communicational components, *FA* for fault itself and *i* stands for the number of the assumption.

Calculation Method (CM). Each approach uses a different calculation method for detecting a fault. A fault may be detected by a threshold test, or by complex inferences based on a specific probability model with temporal and spatial correlation considered. Message exchanging may also happen during inferencing. Some calculations based on inference are carried out in an iterated way, which means some information may be collected again and again until the calculation converges. The information collection usually occurs within temporal or/and spatial correlated nodes.

Table 2 Assumptions in fault detection approaches for WSNs

Label	Description
ASMP-FU-1	The computation for decision making is fault-free
ASMP-FU-2	The sensor nodes are mobile
ASMP-FU-3	The sensor nodes are heterogeneous
ASMP-IN-1	There is a correlation between sensor readings
ASMP-CO-1	The communication channels are fault-free
ASMP-CO-2	The network has a specific topology
ASMP-CO-3	The network needs a certain degree of nodes
ASMP-FA-1	The fault is static
ASMP-FA-2	There is a correlation between faults

Output Range (OR). This states the fault status of the fault detection method. The content, format and size are always application-specific, but the range of the output is related to the network structure. For example, in flat networks without hierarchy, the output is usually about the node itself. On the contrary, in hierarchical networks, like a tree-based, the fault status may concern the children or the parents of the node.

3 Evaluation of Fault Detection Approaches

In this section we introduce a set of evaluation criteria which will be used to evaluate the selected fault detection approaches. Next we present the tables with the obtained data of the selected approaches. Finally we analyze the energy-efficiency and the performance of the fault detection approaches, by using the data from the tables and the evaluation criteria.

3.1 Evaluation Criteria

A fault detection approach can be evaluated as an algorithm, from its computation complexity, correctness, robustness and etc. Mahapatro et al. [22] analyze several terminologies, including correctness, completeness, consistency, latency, computational complexity, communication complexity, diagnosability, detection accuracy, false alarm rate. In this paper, we adopt the following application-independent criteria, which we consider the most relevant ones:

- *Detection Accuracy (DA):* the ratio of the number of faulty nodes detected to the actual number of the actual number of faulty nodes in the network.
- *False Alarm Rate (FAR)*: the ratio of the number of fault-free nodes detected to the actual number of of fault-free nodes in the network.
- *Communication Complexity (COMM)*: the number of messages exchanged in a given network structure in WSN used for detecting faults.

Besides application-independent criteria, there are several application-dependent criteria. Such criteria are the Fault Type (FTYPE), which is what types of fault the approach is able to detect. In WSNs, faults are categorized into different types according to different viewpoints. Ni et al. [27] classify faults with *data-centric* and *system-centric* views. Mahapatro et al. [22] discuss fault types according to the view of *fault-tolerant distributed systems* (Crash, Omission, Timing, Incorrect Computation, Fail-Stop, Authenticated Byzantine, Byzantine faults) and *duration* (Transient, Intermittent, Permanent faults). In this paper, we classify fault types with a more general view according to the *components* of WSNs. Here we mainly focus on three major parts: software and hardware of sensor nodes as functional components, sensor readings as informational components, and networking part as communicational components. Accordingly, there are *Functional Faults (F)*: every hardware or software malfunction which prevents the sensor node to deliver the requested services. *Informational Faults (I)*: sensor readings that are correctly sent from a sensor node, but deviates from the true value of the monitored phenomenon. *Communicational Faults (C)* caused by the network component of the WSN. We also consider some other application-dependent criteria, namely Message Exchange Pattern (MEP) and Communication Range (CR) (Sect. 2.1), and Assumptions (ASMPs), Calculation Method (CM), and Output Range (OR) (Sect. 2.2).

3.2 Evaluation Data

We organize the data extracted from the selected papers in Table 3. The first row list the application-dependent and application-independent evaluation criteria mentioned in Sect. 3.1. Table 4 illustrates the notation for the COMM criterion and Table 5 lists the assumptions of each approach.

3.3 Analysis

To evaluate the energy efficiency of each approach we focus on the relationship between those design considerations listed as different columns in Table 3 and the COMM criterion.

COMM vs. Topology. Some fault detection approaches work with a specific topology (ASMP-CO-2). We focus on *cluster-based* and *tree-based* topology. The tree-based topology requires less messages to complete a fault detection.

COMM vs. MEP. In most cases, the approaches which use active probing as MEP consume more energy. The reason is also obvious, because they require more messages to complete a fault detection and consequently, more energy.

COMM vs. CM. The CM may also affect the energy-efficiency of the process. Here we evaluate three CMs *Bayesian Network-based*, *Message Coordination Protocol*, and *Threshold Test*. The Bayesian network-based CMs use basic principles from the Bayesian network model. The Message Coordination Protocol are based on message exchanging e.g. periodic test with "Hello-IAmAlive" messages. The last category of CMs is based on threshold tests to detect a fault. Regarding the CMs based on Bayesian networks, they appear to be the most energy efficient. Many of them are based purely on a mathematical model and the result is calculated locally. The fact that there is no need of extra messages makes these CMs energy-efficient. The threshold-test CMs are consuming more energy than the previous category. The reason for the increased energy consumption is that the threshold tests are disseminated after being calculated and need extra information to be calculated. The message coordination protocol CMs consume more energy than the previous two categories because it functions with messages which increase in great degree the energy consumption and makes them the least energy efficient between the three categories of CMs.

Performance Analysis. To evaluate the performance of each approach, we investigate the relationships between DA and FAR and some other key criteria.

DA and FAR vs. Topology. The topologies we consider are *cluster-based* and *tree-based*. Figure 1 depicts the mean values regarding the performance of these two topologies. As we can see the approaches using tree-based topology seem to present slightly higher DA but also slightly higher FAR.

DA and FAR vs. Message Exchange Pattern. We calculate the mean value of DA

Table 3 Evaluation data extracted from fault detection approaches

Paper	FTYPE	MEP	MD	CR	CM	OR	DA	FAR	COMM
[35]	I	N/A	Sufficient statistics	Leader node-collaborators	Markov linear state	Cluster	0.88	N/A	$N(H + reading)$
[4]	I	AP	Hello, location, readings	Neighbourhood	Weighted voting	itself	>0.8	<0.2	$N(H)+Nn(H)+Nn(H+double)Nn(H + bool)$
[34]	I	PO	Readings	Node-Sink	Expectation maximization algorithm	Itself	0.95	0.05	$N(H + reading)$
[29]	I	PO	Binary decisions	Fusion center	Threshold test	Itself	N/A	<0.05	$ND(H + reading)$
[6]	I	AP	Readings	Neighbours pairwise	Group voting	Itself	>0.926	<0.014	$Nn(H + reading) + Nn(H + bool)$
[14]	I	PO	Readings (vectors)	Pair-wise	Posterior probability	Itself	>0.73	N/A	$N(H + reading) + N(H + array)$
[5]	I	PO	Readings	Central server	Hierarchical Bayesian space time modelling	Itself	>0.7	0.04 – 0.07	$N(H + reading)$
[25]	I	PO	Readings	Node-Fusion center	Bayesian Networks, Neyman Person	N/A	0.7	0.11	$N(H + reading)$
[26]	I	PO	Readings	Fusion center	Hierarchical Bayesian space time modelling	Itself	0.686 > 0.965	$0.142 < 0.023$	$N(H + reading)$

(continued)

Table 3 (continued)

Paper	FTYPE	MEP	MD	CR	CM	OR	DA	FAR	COMM
[18, 20]	I	N/A	Readings	Pair-wise	ARX model	Itself	>0.9	N/A	$N(H + reading)$
[19]	I	PO	Readings	Arbitrary group	Group testing, Kalman filtering	Itself	>0.8	<0.02	N/A
[24]	I	AP	Readings	Neighbours	Group voting, time series analysis	Itself	0.8 – 0.92	0.05 – 0.26	$Nn(H + reading) + N(H + reading)$
[38]	I	PO	Readings	Pair-wise	HMM, threshold test	Itself	>0.96	N/A	$N(H + reading)$
[8]	I	PO	Readings, fault reports	Neighbours voting	Neighbour	Itself	>0.8	<0.38	$Nn(H + reading) + fn(H)$
[11]	I	AP	Readings, requests, data	Neighbours	Verifier node mechanism	One hop neighbours	0.88 – 0.98	0.0052	$2(H) + 3N(H) + N(H + reading) + 4N(H + double)$
[7]	I, F	PO	Readings	Neighbours	MRF, correlation with neighbours	Itself	>0.96	<0.01	$Nn(H + reading)$
[33]	I,F	PO	Readings	BS-Nodes	Decision tree J48	Itself	1	0.074	$N(H + reading)$
[3]	F	PO	Readings, test results	Neighbours	Neighbour readings comparison	Itself	>0.97	<0.0025	$Nn(H + reading) + 3Nn(H + double)$
[37]	F	PO	Hello, location, energy, ID	Cluster	Threshold test	Itself	N/A	N/A	$Nn(H{+}double){+}M(H{+}double)$

(continued)

Table 3 (continued)

Paper	FTYPE	MEP	MD	CR	CM	OR	DA	FAR	COMM
[16]	F	PO	Fault status, useful data	Neighbours	Threshold test decision dissemination	Itself	>0.91	<0.1	$Nn(H + boolean)$
[9]	F	PO	Detection status	Neighbourhood	Based on [3]	Itself	>0.94	N/A	$Nn(H + reading)$
[36]	F	AP	Test packet	Cluster	Comparing test results	Itself	N/A	N/A	$2 * D * LN * (H)$
[12]	F	PO	Notify packet	Cluster	Notify packet declares if the node is alive	Itself	N/A	N/A	$2N(H) + fn(H)$
[15]	F	PO	End-to-End delay, readings	Node-Sink	Centralized naive Bayes Detector	Network, itself	>0.6	<0.05	$N(H + reading)$
[23]	F,C	PO	22 metrics, readings	BS-nodes	Temporal/Spatial correlation in system metrics	BS range	N/A	N/A	$Nn(H + reading)$
[28]	F,C	PO	Readings	BS-Nodes	Failure knowledge library	Itself	$>0.9^1$ 0.75^2	$>0.35^1$ 0.3^2	$N(H + reading)$
[2]	F,I	AP	Hello packet	Within CHs	Request-reply message mechanism	Itself	0.9	N/A	$2CH(H)$
[31]	F,C	AP	Scenario data input/output	Observer-BS, BS-nodes	Time constraints check	Itself	N/A	N/A	$2OB(H + double) + 2N(H + double)$

(continued)

Table 3 (continued)

Paper	FTYPE	MEP	MD	CR	CM	OR	DA	FAR	COMM
[17]	F,C	PO	Readings, useful data	One hop	Fault detection based on FSM	Itself	>0.9	<0.1	$N(H + double)$
[13]	F,C	AP	Readings, test results	Neighbours	Threshold test, evaluation from neighbours	Itself	N/A	N/A	$N(H + double)$
[40]	F,I,C	PO	Uniform distribution	Neighbours	Threshold test	Itself	1	N/A	$Nn(H + double)$
[21]	F,C	AP	Beacons, local evidence	Parent children	Naive Bayesian classifier, evidence fusion	Parent, children	>0.86	<0.16	$fn(n(2H) + (LN(2H) + m(H + char) + M(h) + (H)))$

Table 4 Notation for evaluating the COMM criterion

H	Header
M	Number of the parents
m	Number of the children
N	Number of the nodes in the WSN
n	Number of the nodes in the neighbourhood
CH	Number of the Cluster Heads
reading	The sensor measurement
ff	Number of fault free nodes
fn	Number of faulty nodes [2, 8]
D	Depth of the tree [36]
LN	Leaf nodes [36]
OB	Number of observer nodes [31]
int	integer variable
array	array variable
bool	boolean variable
double	double variable
char	char variable

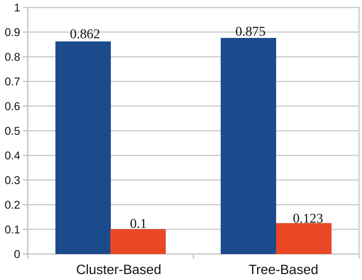


Fig. 1 DA/FAR vs topology

and FAR of the approaches which use PO and AP (Fig. 2). Those using PO have slightly lower DA and higher FAR.

DA and FAR vs. Calculation Method (CM). The CMs we consider are the same as those in the previous part. We can see in Fig. 3 that the threshold test CMs have the highest accuracy and the CMs based on Bayesian network have the lowest DA. Regarding the FAR the Bayesian network CMs have the lowest and the CMs based on message coordination protocols have the highest.

DA and FAR vs. Correlation Assumption. In Fig. 4, we examine how the correlation of the sensor readings (ASMP-IN-1) can affect the performance of an approach. When we adopt ASMP-IN-1, we can achieve higher results in detection accuracy, although the false alarm rate is slightly increased also.

Table 5 Assumptions (ASMPs) of Fault Detection Approaches

Paper	FU_1	FU_2	FU_3	IN_1	CO_1	CO_2	CO_3	FA_1	FA_2
[4]	Y	N	N	Y	Y	Y	N	Y	N
[9]	Y	N	N	Y	Y	N	Y	Y	N
[18, 20]	Y	N	N	Y	Y	N	N	Y	N
[23]	Y	N	N	Y	Y	Y	N	Y	N
[14]	Y	N	N	Y	N/A	Y	N	Y	N
[5]	Y	N	N	Y	N/A	N	N	Y	N
[25]	Y	N	N	Y	N/A	N	N	Y	N
[26]	Y	N	N	Y	Y	N	N	Y	N
[29]	Y	N	N	N	Y	N	N	Y	N
[15]	Y	N	N	N	N	N	N	Y	N
[34]	Y	N	N	N	N	Y	N	Y	N
[28]	Y	N	N	N	N/A	N	N	Y	N
[33]	Y	N	N	Y	N	N	N	Y	N
[37]	Y	N	N	Y	Y	Y	N	Y	N
[36]	Y	N	N	N	N	Y	N	Y	N
[12]	Y	Y	N	N	N/A	Y	N	Y	N
[2]	Y	N	N	N	N	Y	Y	Y	N
[31]	Y	N	N	N	N	N	N	Y	N
[17]	Y	N	N	N	N	N	N	Y	N
[16]	Y	N	N	Y	N/A	N	Y	Y	N
[19]	Y	N	N	Y	Y	N	N	Y	N
[3]	Y	N	N	Y	Y	N	Y	Y	N
[13]	Y	N	N	Y	N	Y	N	Y	N
[6]	Y	N	N	Y	Y	Y	N	Y	N
[40]	Y	N	N	Y	N	N	N	Y	N
[24]	Y	N	N	Y	N	N	N	Y	N
[21]	Y	N	N	N	N	Y	N	Y	N
[8]	Y	N	N	Y	Y	N	N	Y	N
[7]	Y	N	N	Y	N/A	N	N	Y	N
[35]	Y	N	N	N	N/A	Y	N	Y	N
[38]	Y	N	N	Y	N/A	N	N	Y	N
[11]	Y	N	N	Y	N	Y	Y	Y	N

Fig. 2 DA/FAR vs. MEP

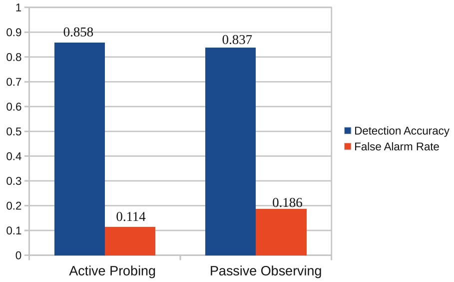


Fig. 3 DA/FAR vs. CM

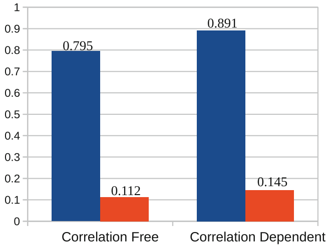
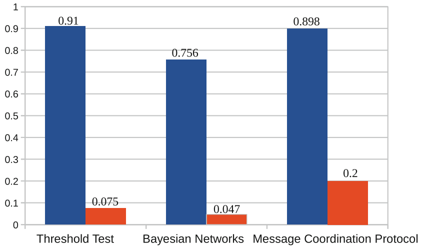


Fig. 4 DA/FAR vs. ASMP-IN-1



4 Design Guidelines

Designing an appropriate fault detection method for a WSN is a not easy task. Since WSN applications are dependent on the requirements and on the deployment environment, each fault detection method should be designed regarding application specific criteria.

Over the selected approaches the topologies we examined are the cluster-based and the tree-based. An advice regarding the topology is that the tree-based may consume less energy than a cluster-based. If a designer has the option to choose between the two MEPs, the PO is the more energy efficient one. The CMs we distinguish over the selected approaches are the *threshold-test, Bayesian Network-based* and *message coordination protocol*. The Bayesian Network-based CM resulted to be more energy efficient than the others.

Regarding the performance, the topology in fault detection approaches cannot offer tremendous changes, but between the cluster-based and tree-based topologies, the former may have slightly lower FAR and the latter little more DA. Regarding the option of the Message Exchange Pattern, by using the Passive Observing we may have lower FAR but for having slightly higher DA we have to use the Active Probing. According to the selected fault detection approaches, the Calculation Method which offer the higher DA is the threshold test and the one which offer lower FAR is the Bayesian networks. We have to mention that the CMs we consider are the same as the previous section.

Finally, if the design is based on the correlation of the sensor readings, it will have higher DA but slightly higher FAR.

5 Conclusion

This paper complements current literature on fault detection methods for WSNs by adding a perspective on energy efficiency, as this represents a key aspect of future Human-Centric WSNs. In particular, we have proposed a two-phase fault detection process, information collection and decision making, with emphasis on figuring out where and when message exchanging occurs. After defining application-independent and application-dependent evaluation criteria, we have investigated the relationships between some major design factors and performance parameters and also summed up some design guidelines.

Acknowledgments This paper has been supported by the China Scholarship Council during Yue Zhang's visit at DTU in the context of the IDEA4CPS project and National Natural Science Foundation of China (No. 61361136002).

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