Towards a Composition of Region-Adherent Systems

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Abstract—**Graceful degradation entails a loss of functionality or reduction in the service quality that a system provides in response to faults. One new form of graceful degradation, which is called region adherence, upper-bounds the violation of safety due to faults *in space*. Bounding in space means that the decrease of service quality, which the system provides to its environment, is upper-bounded per fault. In this paper, we investigate the effect of composing region-adherent systems such that the resulting system is also region-adherent. We analyze the service quality of region-adherent wireless sensor networks, which are structured according to different topologies. We cover all possible fault scenarios and analyze their impact on differently structured networks by calculating the minimal, the average, the standard deviation, and the variance of the resulting service qualities.**

Keywords–Wireless Sensor Networks; Service Quality; Fault Tolerance; Graceful Degradation; Region Adherence.

I. INTRODUCTION

Nowadays, the increasing use of computers in almost every field of modern life has led to a need for highly dependable computer systems. Fault tolerance is a well-known approach by which the dependability of computer systems can be increased. [1] The goal of fault tolerance is to provide the intended service of a system despite the presence of faults in the system. Graceful degradation [2] is one of the possible concepts to realize a fault-tolerant system. In graceful degradation, the execution of the system continues but in a “degraded” mode. A “degraded” mode is a limited functionality or performance of the system even when a large portion of the system has been destroyed or rendered inoperative.

Region adherence [3] is a particular form of graceful degradation: a system may be implemented based on a distributed algorithm that employs redundancy to bound the observable, incorrect behavior of the system *in space*. With “bounding in space,” it is meant that the decrease of the quality of the service, which the system provides to its environment, is upper-bounded per fault. We call such an algorithm (resp. the system implementing it) *region-adherent*. Let f be the maximal number of faults a system is able to withstand. Then, a region-adherent system – per fault – gracefully degrades the service quality provided by the system. It does so up to some maximal number of faults. Additionally, degradation is upper-bounded per fault. A region-adherent system exhibits very desirable fault tolerance properties as it provides *quantified service quality guarantees* in case up to f faults happen. Thus, at any time, knowing the number of faults that already have occured, the system user can take an *a priori*-known minimal service quality for granted: a very valuable information in various critical settings. Examples of region adherent systems are presented in [3] and [4] along with a formal definition of region adherence and formal techniques for proving the region adherence property. Becker et. al. [3] introduced the concept of region adherence and presented a Wireless Sensor Network (WSN) for monitoring the air humidity in some geographical region. In this WSN, a region-adherent algorithm is used that helps to quantify the effects of failed sensors in the sensing process of the WSN. A simple refinement of the lower bounds of the service quality known of a region-adherent system is presented in [5].

The main idea of this paper is to compose region-adherent systems out of region-adherent subsystems and analyze the impact of faults on the service quality of the resulting (region-adherent) system. For this purpose, we investigate five tree-shaped WSN topologies, each with nine sensor nodes subject to faults. We show that, for these particular examples, the parallel composition of the subsystems lead to a higher average of service quality than composing the subsystems in hierarchical fashions. Furthermore, we gain the best results by distributing the sensor nodes between the parallel subsystems as equally as possible.

The paper is structured as follows. In the next section, we briefly introduce the notion as well as a formal definition of region adherence together with closely related notions needed for the understanding of the presented material. In Section III, we give a general formula for calculating the average service quality of a region-adherent tree-shaped WSN. Section IV analyses five compositions of region-adherent WSNs based on tree-shaped topologies with nine sensor nodes each using the general formula. In Section V, we summarize the results of the paper.

II. NOTION OF REGION ADHERENCE

The basic idea of the region adherence concept is to restrict the safety property invalidation of a system *in space*. This is achieved by upper-bounding the reduction of the service quality of a system *per fault up to some maximal number of faults*. It is important to note that region-adherent systems can only by realized, if the possible faults which might occur (i.e., the faults of the underlying fault model) may not transfer a system from a given state to *any other state* in the system state space.

For an example of the fault-tolerant behavior of a region-adherent system, refer to Figure 1. The dashed blue line shows the service quality of the region-adherent system in a particular execution of the system. The solid blue line (i.e., the “staircase-like graph”) states the *minimal* service quality guaranteed by the system. Irrespective of a particular execution, the system’s service quality *always* remains on or above the minimal service quality represented by the “staircase-like graph.” In the example, the system is initially in a safe state. In a safe state, it always delivers 100% of service quality. After the first fault has occurred, the system must deliver a service quality of at least $100\% - \alpha$. Note that the dashed line actually exhibits a slightly higher service quality. This is possible for a particular execution but may not generally hold. After the second fault, the guaranteed and delivered service quality is again reduced, but it becomes not lower than $100\% - \alpha - \beta$. After the third fault, the guaranteed service quality is at least $100\% - \alpha - \beta - \gamma$.

Figure 2 gives a topological interpretation of a region-adherent system: here, the blue dashed line, again, represents a particular execution of the region-adherent system over time. The execution starts in the innermost region where the system exhibits 100% of service quality. When the first fault occurs, the system is thrown into a state of the neighboring region with only $100\% - \alpha$ service quality. The next fault lets the system enter a region with only $100\% - \alpha - \beta$ service quality and so on. When being in a particular region – without any further fault occuring – the system is allowed to stay within the region, it is currently in, as well as in any included region. In this sense, the system behavior is *restricted in space*, i.e., it must *adhere to regions* of known system quality. We formally define the notation of region adherence as follows [6]:

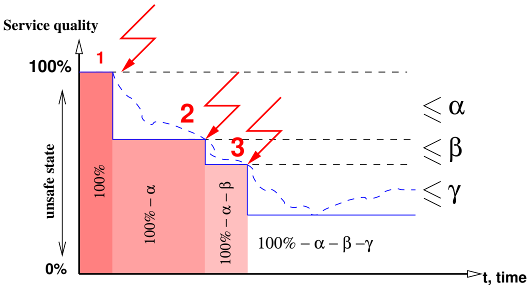

Figure 1. Worst case (solid blue line) and particular behavior (dashed blue line) of a region-adherent system after one, two, and three faults over time with $\alpha, \beta, \gamma > 0$.

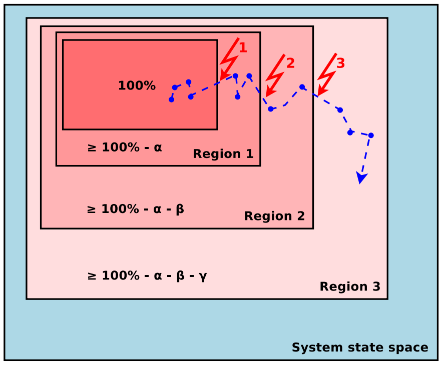

Figure 2. Topological interpretation of a region-adherent system with $\alpha, \beta, \gamma > 0$. The dashed blue line represents a particular execution of the system where three faults occur.

Definition 1 (General Region Adherence of a System): We assume a system with configurations C, initial configurations C_0 and algorithm A under fault model F. Let $g : C \mapsto [0,1]$ be a function stating the service quality of the system and let f be a natural number. $r : \{0, \ldots, f\} \mapsto [0,1)$ is a non-decreasing function with $r(0) = 0$ and $r(f) < 1$.

Algorithm A is called *f-region-adherent wrt.* g, r, and F, if and only if for all reachable configurations $c \in C$, all initial configurations $c_0 \in C_0$ and all executions $\gamma = c_0 \cdots c$ ending in c with $\#_{F \setminus A}(\gamma) \leq f$, the following holds:

$$g(c) \geq 1 - r\left(\#_{F \setminus A}(\gamma)\right), \tag{1}$$

where $\#_{F \setminus A}(\gamma)$ represents the number of fault steps of execution γ.

Figure 3 gives an example of an execution γ of the system. In this execution, three faults occur. Thus, $\#_{F \setminus A}(\gamma)$ is 3. A system executing an f-region-adherent algorithm is also called f-region-adherent. The value of g may be interpreted as a percentage. The function r can be perceived as the service's *loss* or *reduction of quality* with $r(i)$, $0 \leq i \leq f$, upper-bounding the loss due to the i-th fault. Note that an f-region-adherent system is able to tolerate at least f faults and is still exhibiting a service quality higher than 0%.

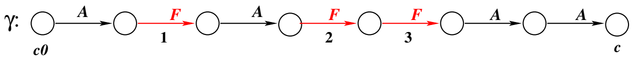

Figure 3. Example of an execution γ.

A particular subclass of region-adherent algorithms is called *α-equidistance*. It allows the classification of region adherence based on a simple service quality reduction function r. Furthermore, algorithms can often more easily be proven α-equidistant than region-adherent in general. This is due to the proof scheme adopted (see Becker et. al. [4]).

Definition 2 (α-Equidistance): An algorithm A that is f-region-adherent wrt. g, r, and F with

$$r(i) = \alpha \cdot i, \qquad 0 \leq i \leq f, \tag{2}$$

is called *α-equidistant f-region-adherent*.

For an α-equidistant algorithm, $1/f > \alpha > 0$ trivially holds.

In the next section, we present a formula for calculating the service quality of a tree-shaped sensor network. This formula is the extension of a formula presented in [3] for the arithmetic mean of sensor values to sensor systems which are composed of different subsystems. We use this formula for the calculation of the service quality of region-adherent WSNs presented in Section IV.

III. CALCULATION OF THE SERVICE QUALITY OF REGION-ADHERENT TREE TOPOLOGY NETWORKS

The systems under consideration consist of gateway nodes (also called *sink* nodes), which collect the data of all connected *sensor* nodes. Sensor nodes produce or sense the data, the gateway nodes as well as the system users are interested in. Gateway and sensor nodes form a (communication) network. This network is of a tree topology. Sensor nodes form the leafs of the tree topology and the only or the multiple gateway nodes form the root and the inner nodes (if any) of the tree topology. We call such systems *sensing tree networks*.

Since gateway nodes, in our setting, are realized by much more dependable hardware components, gateway nodes are assumed to be failure-free. Sensor nodes, on the contrary, are realized by cheap, unreliable hardware. They are assumed to be subject to faults leading to failures. If a sensor node fails, then we assume a fail-fast failure semantics. In subsequent figures, sink nodes are depicted as black circles whereas sensor nodes are represented by white circles.

In the following, we define a sensing tree network formally.

Definition 3 (Sensing Tree Network (with Failures)): A tuple $S = (N, B, W, T, b)$ with a set of *nodes* N, a set of *gateway* nodes $B \subseteq N$, a set of *sensor* nodes $W \subseteq N$, a *transition relation* $T \subseteq B \times N$, and an *initial* node $b \in B$ is called *sensing tree network*. For T, we demand two constraints. Firstly, for every two nodes $n_1, n_2 \in N$ with $n_1 \neq n_2$ there must exist exactly one path between n_1 and n_2. Secondly, for every $b \in B$ there must be a node n with $(b, n) \in T$.

For a set of *faulty nodes* $F \subseteq W$, we call $S = (N, B, W, T, b, F)$ a *sensing tree network with failures*.

As an example, the sensor network depicted in Figure 4 is defined as $S_A = (\{s_0, s_1, \ldots, s_9\}, \{s_0\}, \{s_1, \ldots, s_9\}, \{(s_0, s_i) \mid s_i \in W\}, s_0)$, with s_0 as the given root gateway node.

In our setting, the sensors are distributed in a (small) geographical region, but should sense redundantly the same data.

For a given sensing tree network with failures $S = (N, B, W, T, b, F)$, we assume that each sensing node $w \in W$ delivers a value $v(w) \in [0, u]$ for a given bound u. Let V denote the exact value which should have been sensed, then each correctly sensed value can deviate from this value by at most $\epsilon > 0$. Since we only want to investigate the impact of a faulty node on the service quality in different topologies, we abstract from drawing the value of a faulty node randomly but consider its value to be zero. Thus,

$$v(w) \in \begin{cases} [0, 0] & \text{if } w \in F \\ [V - \epsilon, V + \epsilon] \cap [0, u] & \text{otherwise} \end{cases}$$

For collecting all child nodes of a given gateway node, we define the function $c : B \to \mathbb{P}(N)$ with $c(b) = \{n \in N \mid (b, n) \in T\}$.

The *mean value of a gateway node* is calculated by $\tilde{v} : B \to \mathbb{Q}$ with

$$\tilde{v}(b) = \frac{1}{|c(b)|} \cdot \left(\sum_{w \in c(b) \cap W} v(w) + \sum_{b' \in c(b) \cap B} \tilde{v}(b') \right). \quad (3)$$

Since all sensors should sense the same value, we estimate their value by calculating the arithmetic mean. The left summand calculates the sum of the values of the sensor nodes directly connected to the gateway node. If a gateway node has other gateway nodes as children by itself, we calculate their value recursively and sum them up in the right summand. The mean value of a gateway node is this sum divided by the number of all children.

We now calculate the *service quality of a sensing tree network with failures* $S = (N, B, W, T, b, F)$ analogously to the approach presented by Becker et. al. [3] for only one gateway node:

$$g(S) = min \left\{ 1 - \frac{|\tilde{v}(b) - V| - \epsilon}{u}, 1 \right\} \quad (4)$$

For comparing the impact of failures on differently structured sensing tree networks, we calculate the mean of all possible occurrences of failures (i.e., failure scenarios). For a sensor tree network $S = (N, B, W, T, b)$ and f failures, we define the set of all possible sensing tree networks with failures as $SF(S, f) = \{(N, B, W, T, b, F) \mid F \subseteq W \wedge |F| = f\}$. This means that $SF(S, f)$ contains all possible failure scenarios of a given sensing tree network with a fixed number f of failures. Thus, we can use the binomial coefficient $\binom{|W|}{f}$ to calculate $|SF(S, f)|$, since we consider all distinct subsets with f elements of the set of all sensor nodes W.

The *mean service quality of a sensing tree network* $S = (N, B, W, T, b)$ *with* f *failures* is then calculated by

$$\tilde{g}(S, f) = \sum_{S_F \in SF(S, f)} \frac{g(S_F)}{|SF(S, f)|} \quad (5)$$

This means that we sum up the service quality of a sensing tree network for each possible failure scenario having exactly f failures and divide them by the number of all possible failure scenarios.

The next section exploits these formulas for analyzing five compositions of sensing tree networks by their service quality despite the occurrence of failures.

IV. SIMULATION AND EVALUATION OF SENSING TREE NETWORKS

As an example, we assume a WSN for measuring the air humidity. The WSN consists of $n = 9$ sensor nodes that independently measure the air humidity in some (small) geographical region. The sensor nodes send the measured values to some gateway node. We make the following assumptions in our simulations and analyses:

1) sensor nodes work independently of each other, they do not communicate with each other and independently send their values to a gateway node,
2) gateway nodes are failure-free,
3) sensor nodes fail independently of each other,
4) failing sensor nodes do so with fail-silent failure semantics.

A. Test Setup:

We compose the WSN in a variety of tree-shaped typologies. For each topology, we simulate faults at all possible positions and for all possible combinations of positions. For all possible combinations of a fixed number of i failures, $0 \leq i \leq 8$, we calculate the service quality of the whole network using Formula 4, assuming a true air humidity value V of 0.6, a deviation $\epsilon = 0.03$ of a sensor node from true air humidity as well as an upper-bound sensor value u of 0.75. (The particular semantics of this air humidity value is not important in the scope of this paper.) To analyze the simulation results, we calculate the minimal, the average, the standard deviation, and the variance for each number of possible faults of sensor nodes.

B. Test Results:

Topology A: The WSN in Figure 4 has nine sensor nodes which form a 2-level tree network with the gateway node as its root. This arrangement represents Topology A. According to Definition 2, the WSN is 8-region-adherent and α-equidistant with $\alpha = 1/9$. In this topology, obviously, all sensor nodes reside on the same level. As said, we consider all possible combinations of sensor node failures and calculate the minimal, the average, the standard deviation, and the variance of the service quality.

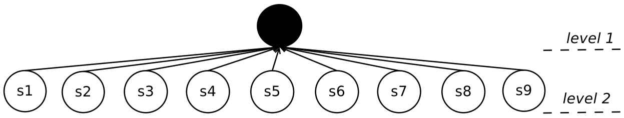

Figure 4. Topology A: WSN with two levels, one gateway node and $n = 9$ sensor nodes. All sensor nodes are on level 2 whereas the gateway node forms the root of the network on level 1.

For example, there are nine failure scenarios where exactly one sensor node fails and 36 failure scenarios with exactly two failures. The results for a WSN using Topology A are given in Table I. For this topology, the standard deviation is very small, since all sensor nodes are positioned on the same level within one group. Thus, any subset of sensor nodes failing conceptionally has the same impact on the reduction of service quality. This can more obviously being seen in Figure 5.

TABLE I. TEST RESULTS OF THE WORST CASE, THE AVERAGE, THE STANDARD DEVIATION, AND THE VARIANCE OF THE SERVICE QUALITY OF A WSN AFTER EACH NUMBER OF FAULTS FOR TOPOLOGY A.

# of Faults	Minimal Service Quality	Average Service Quality	Standard deviation	Variance
0	1.0	1.0	0.0	0.0
1	0.9384	0.9484055471	$3.507 * 10^{-5}$	0.00592
2	0.8318	0.8528330018	$6.590 * 10^{-5}$	0.00811
3	0.7421	0.7570313619	$4.484 * 10^{-5}$	0.00669
4	0.6449	0.6620351405	$3.947 * 10^{-5}$	0.00628
5	0.5516	0.5654450820	$2.983 * 10^{-5}$	0.00546
6	0.4608	0.4719918291	$2.198 * 10^{-5}$	0.00468
7	0.3686	0.3759426946	$1.368 * 10^{-5}$	0.00369
8	0.2770	0.2801876536	$6.472 * 10^{-6}$	0.00254

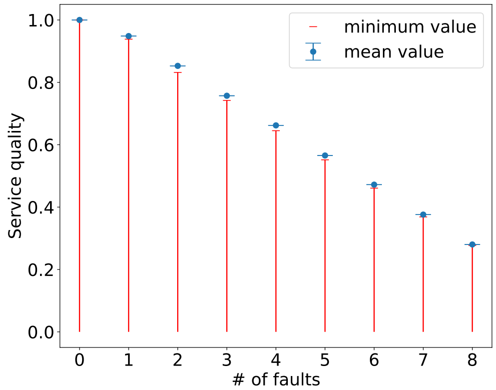

Figure 5. Average and minimal service quality together with standard deviation error bars for a WSN according to Topology A.

Topology B: Here, we consider a 3-level tree topology of the form given in Figure 6. Four sensor nodes together with an additional gateway node are placed on level 2. The additional gateway node manages five sensor nodes on level 3. These five sensor nodes together with their gateway node form a subsystem with a topology similar to Topology A. A WSN using Topology B can be perceived as a WSN that is composed hierarchically by a "parent" system on levels 1 and 2 – which is 3-region-adherent – and a subsystem, which is 4-region-adherent. The entire system obviously is 8-region-adherent.

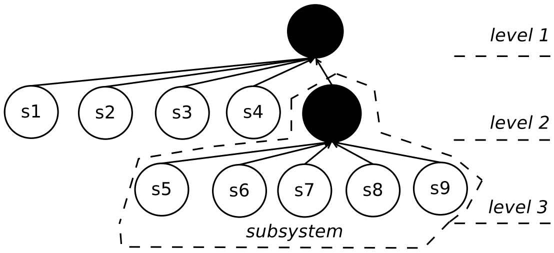

Figure 6. Topology B: WSN with three levels and $n = 9$ sensor nodes. The five sensor nodes on level 3 together with a gateway node on level 2 form a subsystem.

Again, we inject an increasing number of faults into the system and calculate the minimal, the average, the standard deviation, and the variance of the service quality. The results are given in Table II. It can be seen that the possibility of faults occurring on different levels impact the service quality of the system differently, compared to faults in Topology A: faults occurring on a lower level (i.e., level 3) have less an impact on service quality than faults occurring on a higher level (i.e., level 2) of the system. This fact leads to higher standard deviations and variances than in Topology A. This can also be seen in Figure 7. When comparing the minimal service qualities obtained by Topology A and B, we see that in all non-trivial cases, Topology A outperforms Topology B.

TABLE II. TEST RESULTS OF THE WORST CASE, THE AVERAGE, THE STANDARD DEVIATION, AND THE VARIANCE OF THE SERVICE QUALITY OF A WSN AFTER EACH NUMBER OF FAULTS FOR TOPOLOGY B.

# of Faults	Minimal Service Quality	Average Service Quality	Standard deviation	Variance
0	1.0	1.0	0.0	0.0
1	0.8662	0.9438916178	0.0037	0.06090
2	0.6966	0.8524241592	0.0080	0.08958
3	0.5189	0.7571151734	0.0110	0.10501
4	0.3534	0.6620938031	0.0116	0.10799
5	0.3219	0.5667667375	0.0115	0.10753
6	0.2857	0.4717086893	0.0105	0.10295
7	0.2525	0.3756783898	0.0080	0.08970
8	0.2185	0.2806518074	0.0045	0.06780

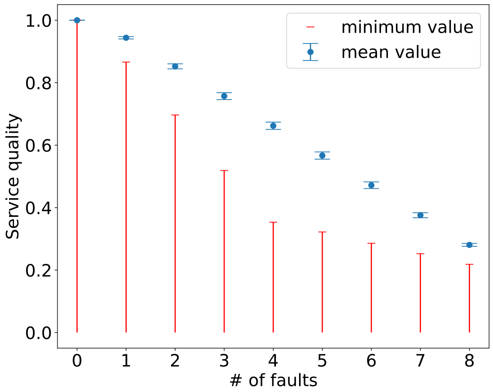

Figure 7. Average and minimal service quality together with standard deviation error bars for a WSN according to Topology B.

Topology C: This topology consists of three subsystems of identical nature composed in a parallel manner (see Figure 8)

A subsystem consists of a gateway node on a higher level and three sensor nodes on the next lower level. The three subsystems together with an additional gateway node, acting as root, form the 3-level topology. Note that within the three subsystems, sensor nodes are evenly distributed. Each subsystem is 2-region-adherent and the entire system is, again, 8-region-adherent. The test results are given in Table III and Figure 9.

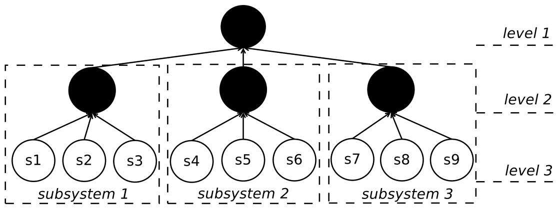

Figure 8. Topology C: WSN with three levels and $n = 9$ sensor nodes. Three subsystems of identical size are composed in a parallel fashion to form a new system.

Although Topology C differs from Topology A as Topology C composes three subsystems in a parallel manner (as opposed to composing nine sensor nodes in parallel), the values obtained for service quality, average service quality, standard deviation, and variance are very similar. The particular symmetric grouping of three sensor nodes in three subsystems has only a negligible effect on these measures.

TABLE III. TEST RESULTS OF THE WORST CASE, THE AVERAGE, THE STANDARD DEVIATION, AND THE VARIANCE OF THE SERVICE QUALITY OF A WSN AFTER EACH NUMBER OF FAULTS FOR TOPOLOGY C.

# of Faults	Minimum Service Quality	Average Service Quality	Standard deviation	Variance
0	1.0	1.0	0.0	0.0
1	0.9337	0.9474071917	$5.070 * 10^{-5}$	0.00712
2	0.8381	0.8505722057	$6.499 * 10^{-5}$	0.00806
3	0.7424	0.7573294496	$2.953 * 10^{-5}$	0.00543
4	0.6467	0.6617785970	$3.488 * 10^{-5}$	0.00590
5	0.5534	0.5664461319	$2.848 * 10^{-5}$	0.00533
6	0.4627	0.4718620317	$1.888 * 10^{-5}$	0.00434
7	0.3693	0.3764175436	$1.351 * 10^{-5}$	0.00367
8	0.2764	0.2813692449	$8.467 * 10^{-6}$	0.00290

Topology D: For this topology, we modify Topology C such that the sensor nodes are *not evenly* distributed to the three subsystems. We believe that this homogeneous distribution of sensor nodes to subsystems is responsible for the very low standard deviation and variance of Topology C. Topology D is given by Figure 10. As one can observe, the assignment of the nine sensor nodes to the three subsystems is now somehow "unbalanced." Subsystem 3 is 4-region-adherent, whereas subsystems 1 and 2 are only 1-region-adherent. The whole system is again 8-region-adherent. Table IV and Figure 11 show what we have expected. Topology D is responsible for a severe loss in minimal service quality compared to Topologies A and C. Furthermore, Topology D's standard deviation and variance is also much higher. When comparing the results of Topology D with the results of an hierarchical composition as given by Topology B, one observes that the former outperforms the latter for all non-trivial cases in terms of minimal service quality, standard deviation, and variance.

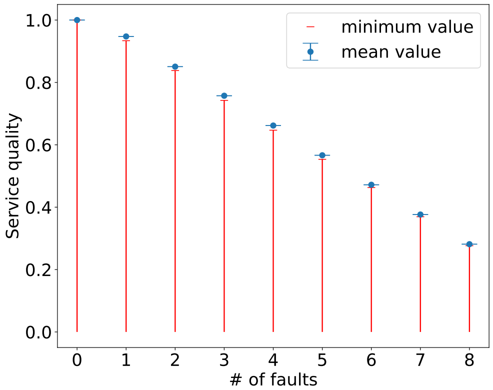

Figure 9. Average and minimal service quality together with standard deviation error bars for a WSN according to Topology C.

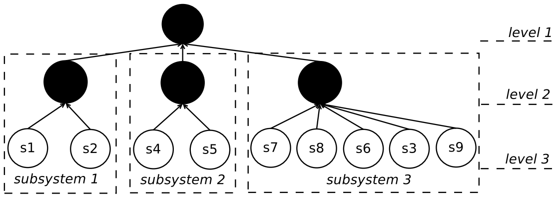

Figure 10. Topology D: WSN with three levels and $n = 9$ sensor nodes, where the sensor nodes are on the same level but not equally distributed among the three subsystems.

Topology E: In this topology, shown in Figure 12, we increase the number of levels by applying a hierarchical composition of systems twice. The resulting topology still has nine sensor nodes in total, but they are distributed on four levels. Within each level, though, the sensor nodes are evenly distributed. A WSN according to this topology can be interpreted as a system that uses a subsystem. This subsystem includes a subsystem (shown as "sub-subsystem" in the figure) of its own. The "parent" system spanning levels 1 and 2, as well as the subsystem and the sub-subsysten, are 2-region-adherent. The entire system is 8-region-adherent.

As we can observe in Table V and Figure 13, the standard deviation and the variance increase again. In particular, they are even higher than the corresponding values of Topology B. Furthermore, the minimal service quality of all non-trivial cases

TABLE IV. TEST RESULTS OF THE WORST CASE, THE AVERAGE, THE STANDARD DEVIATION, AND THE VARIANCE OF THE SERVICE QUALITY OF A WSN AFTER EACH NUMBER OF FAULTS FOR TOPOLOGY D.

# of Faults	Minimal Service Quality	Average Service Quality	Standard deviation	Variance
0	1.0	1.0	0.0	0.0
1	0.8881	0.9479234514	0.0023	0.04891
2	0.7518	0.8535155883	0.0033	0.05829
3	0.6037	0.7565725916	0.0041	0.06452
4	0.4698	0.6612940253	0.0045	0.06727
5	0.4110	0.5664977363	0.0046	0.06830
6	0.3553	0.4720827765	0.0041	0.06423
7	0.2963	0.3751367238	0.0032	0.05683
8	0.2420	0.2821965632	0.0018	0.04298

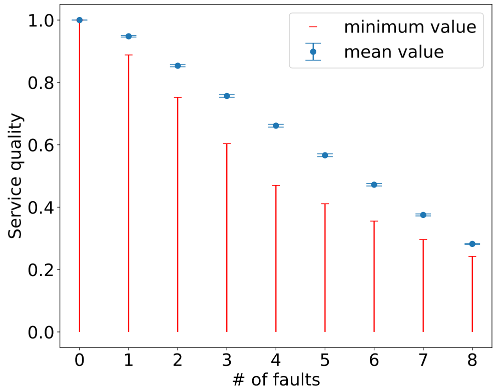

Figure 11. Average and minimal service quality together with standard deviation error bars for a WSN according to Topology D.

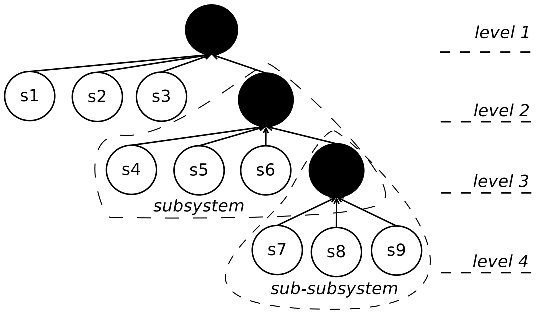

Figure 12. Topology E: WSN with four levels and $n = 9$ sensor nodes.

are the lowest among all topologies investigated. Through the hierarchical composition – introducing various levels where sensor nodes might be placed on – the overall impact of a failing sensor node on the observed measures depends on its level: a sensor node failing on a lower level (having a higher level number) has less an impact than a sensor node failing on a higher level.

V. CONCLUSION

In this paper, we presented a first step towards analyzing the impact of faults on the service quality of differently composed (i.e., structured) region-adherent WSNs. By means of parallel and hierarchical composition, we designed five tree-shaped network topologies. These topologies were subsequently used by WSNs to perform their tasks. Each WSN was – by design – 8-region-adherent. For each topology (and thereby: for each WSN), we calculated the minimal service quality. Furthermore, we simulated all possible fault scenarios and calculated the average, the standard deviation, and the variance of the service quality. The results showed that – depending on the topology – faults can differently impact the minimal service quality and related measures of the system. In particular, the experiments suggest that composing a WSN from subsystems in a parallel fashion leads to better results than composing it hierarchically. Furthermore, the more evenly the sensor nodes are distributed over the subsystems, the less negative is the impact of failures.

TABLE V. TEST RESULTS OF THE WORST CASE, THE AVERAGE, THE STANDARD DEVIATION, AND THE VARIANCE OF THE SERVICE QUALITY OF A WSN AFTER EACH NUMBER OF FAULTS FOR TOPOLOGY E.

# of Faults	Minimal Service Quality	Average Service Quality	Standard deviation	Variance
0	1.0	1.0	0.0	0.0
1	0.8269	0.9428500325	0.0061	0.07837
2	0.6084	0.8517187577	0.0120	0.10988
3	0.4033	0.7591684317	0.0167	0.12945
4	0.3447	0.6617107143	0.0188	0.13727
5	0.2925	0.5669404963	0.0182	0.13499
6	0.2406	0.4723015525	0.0164	0.12812
7	0.2211	0.3751863283	0.0126	0.11241
8	0.2035	0.2817474513	0.0075	0.08663

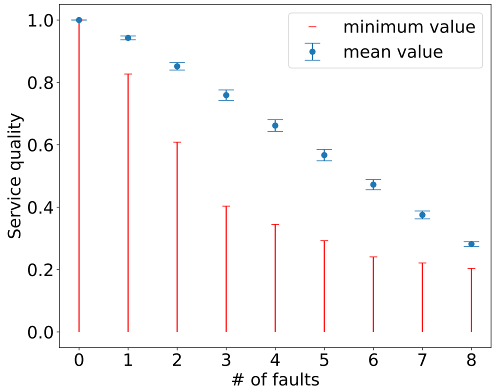

Figure 13. Average and minimal service quality together with standard deviation error bars for a WSN according to Topology E.

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