On the Lifetime of Wireless Sensor Networks

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Abstract

Network lifetime has become the key characteristic to be used for evaluating sensor networks in an application specific way. Especially the availability of nodes, the sensor coverage, and the connectivity have been included in discussions on network lifetime. Even quality of service measures can be reduced to lifetime considerations. A great number of algorithms and methods were proposed to increase the lifetime of a sensor network – based on the particularly selected definition of network lifetime. Motivated by the great differences in existing definitions of sensor network lifetime that are used in relevant publications, we reviewed the state of the art in lifetime definitions, their differences, advantages, and limitations. This survey was the starting point for our work towards a generic definition of sensor network lifetime for use in analytic evaluations as well as in simulation models – focusing on a formal and concise definition of accumulated network lifetime and total network lifetime. We also demonstrate the applicability of our definition based on the surveyed lifetime definitions found in the literature as well as using an example to explain the various aspects influencing sensor network lifetime.

Index Terms

sensor networks, lifetime, connectivity, coverage, longevity

I. Introduction

With the proliferation of wireless sensor networks (WSN), completely new application domains for wireless ad hoc networks have emerged. From wildlife monitoring and precision agriculture to habitat monitoring and logistics applications, there is an increasing demand on developing more efficient sensor networks. Especially the characteristic features of WSN, such as the limitations in the available resources (energy, processing speed, storage), distinguish sensor networks from other ad hoc networks [1]. Besides these restrictions, WSN are also exposed to various requirements, for example the varying density of the node deployment, and possibly hazardous environmental conditions [2]. Many aspects concerning sensor networks have already been investigated [3], e.g. routing and data dissemination schemes [4], self-organization issues [5], the efficient deployment of sensor nodes [6], and the interaction of sensor/actuator networks [7], while others are still work in progress. This includes the study of *network lifetime* as a key characteristic of WSN.

Network lifetime is perhaps the most important metric for the evaluation of sensor networks. Of course, in a resource-constrained environment, the consumption of every limited resource must be considered. However, network lifetime as a measure for energy consumption occupies the exceptional position that it forms an upper bound for the utility of the sensor network. The network can only fulfill its purpose as long as it is considered ”alive”, but not after that. It is therefore an indicator for the maximum utility a sensor network can provide. If the metric is used in an analysis preceding a real-life deployment, the estimated network lifetime can also contribute to justifying the cost of the deployment. Lifetime is also considered a fundamental parameter in the context of availability and security in networks [8].

When studying the lifetime of sensor networks, it is necessary to analyze both the network as a whole and the single nodes making up the network. Sensor nodes consist of an embedded system (micro processor, memory, external storage), communication facilities, and sensors. All these entities contribute to the energy consumption of the sensor node. The amount of energy that can be consumed by a sensor node is limited by its power source, typically a battery. A sensor network consists of a number of these nodes. In such a network, the nodes communicate to form an ad hoc network and are thus able to transmit the collected sensor data to designated sinks. In principle, this is also true if in-network processing mechanisms are employed [9], [10].

Lifetime studies first came up because the recharging or replacement of batteries is not feasible in many scenarios (too many nodes, hostile environment, etc.), and thus the lifetime of the network can not be extended infinitely. Naturally, lifetime was then discussed from different points of view, which led to the development of various lifetime metrics. Depending on the energy consumers regarded in each metric and the specific application requirements considered, these metrics may lead to very different estimations of network lifetime.

In summary, it can be said that although network lifetime is considered as one of the most important parameters to evaluate sensor networks or algorithms to be used in sensor networks, there are still a large number of open issues. This finally motivated us to work on a general definition for sensor network lifetime that can be directly applied in analytical evaluation processes as well as in simulation models.

In this paper, we discuss the need to refer to *network lifetime* as the key characteristic to evaluate the performance of sensor networks. We show that essentially all parameters can be reduced to lifetime considerations. Such parameters include coverage,

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connectivity, and node availability. Based on the analysis of previous lifetime definitions, we propose a more concise definition that can be used in all domains of sensor network research. The primary contributions of this paper can be summarized as follows:

- *Analysis of existing lifetime definitions* – In this part, we provide a survey on network lifetime definitions as well as a comparison based on the selected parameters.
- *Overview of the parameters influencing network lifetime* – We summarize all parameters that affect the lifetime of single nodes as well as the overall network lifetime. It will become obvious that application requirements have to be used to reflect the particular lifetime measures.
- *Concise redefinition of network lifetime* – We conclude the survey and the listed requirements with a formal definition of network lifetime that reflects all needed characteristics of typical sensor networks. We were even able to successfully reduce other measures such as the network quality to lifetime matters.

The developed metrics for network lifetime can be used to evaluate algorithms and methods in a comparable way, if the parameters used in the specific scenario are published.

The remainder of the paper is organized as follows. A survey on lifetime definitions is provided in section II. Afterwards, we discuss open issues and missing features in these lifetime definitions in section III and characteristics of single sensor nodes in section IV, respectively. In section V, we present our more concise definition for sensor network lifetime. Its applicability is demonstrated in section VI based on the survey of lifetime definitions as well as based on an example. Finally, section VII concludes the paper.

II. Related Work on Network Lifetime

In the literature, we can find a great number of relevant publications that address the problem of *sensor network lifetime*. Some papers employ network lifetime as a criterion that needs to be maximized, but never exactly define the term network lifetime. However, the majority of authors do state how network lifetime is defined in the context of their work. Obviously, this leads to a strong diversity of co-existent definitions. In this section, we summarize the most common definitions in form of a survey on lifetime definitions.

A. Network lifetime based on the number of alive nodes

The definition found most frequently in the literature at the moment is n-of-n lifetime. In this definition, the network lifetime T_n^n ends as soon as the first node fails, thus

$$T_n^n = \min_{v \in V} T_v$$

with T_v being the lifetime of node v. Some authors exclude the sink nodes from the node set V to reflect the assumption that a power plug is available at the sink nodes [11]. T_n^n is a very convenient definition. It is easy to compute and the algorithms running in the network do not have to deal with topology changes at all. This is because in a network without mobile nodes – which is by far the most common case considered at the moment – the first node to fail results in the first topology change after the deployment. However, in most cases the lifetime calculated by this metric will be far too short for meaningful evaluation of sensor network applications. For example, consider a node that has several direct neighbors with the same sensing equipment. Most networks will be able to cope with the failure of one node in such a case but the metric can not represent this kind of network redundancy. Therefore, the only case in which this metric can be reasonably used is if all nodes are of equal importance and critical to the network operation as stated by Madan et al. [11].

If n-of-n lifetime is to be used as a comparative metric, another objection usually holds. This definition favors WSN algorithms that ensure a maximum lifetime for each node, i.e. where the first node dies last. This means that algorithms that deplete the given energy most uniformly (where therefore most remaining nodes fail shortly after the first one) are possibly assigned a longer lifetime than those algorithms where a node may fail relatively early, but the network can still provide useful information for a long time after this event. The T_n^n metric is also not adequate for evaluating scenarios that consider hardware failures, because randomly distributed hardware failures might occur very early and thus distort the lifetime measure considerably. In spite of these arguments, many authors, e.g. [12]–[14], adapt this metric without further consideration. Mhatre et al. [15] state that n-of-n lifetime might be a conservative approach, especially for a system with single-hop communication.

A common variant of the T_n^n metric defines the network lifetime as the time until the fraction of alive nodes falls below a predefined threshold β, or the time during which at least k out of n nodes are alive (k-of-n lifetime T_n^k). While this metric is better applicable than n-of-n lifetime, it still lacks accuracy. Consider the case when $k' < k$ nodes at strategic positions (perhaps around the base station) fail and the remaining nodes now have no possibility of transmitting any data to the sink. Then the network should not be considered "alive", but the metric does not recognize this until another $k - k'$ nodes have failed. Again, comparative evaluations cannot be performed using this metric as no statements are made as to where the nodes fail and whether the remaining nodes are still able to transmit data to the sink or to sense events in the region of interest, respectively [16].

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Hellman et al. [17] define another metric based on the number of available nodes. They divide the set of nodes into critical and non-critical nodes and then allow for k node failures in the group of non-critical nodes and no failures at all in the group of m critical nodes. They name this approach m-in-k-of-n lifetime. Nevertheless, the objections as stated for k-of-n still apply.

Another variant of n-of-n lifetime is discussed in the context of clustering schemes [18], [19]. An important assumption for these approaches is that the cluster heads are chosen beforehand – probably as a set of special, more powerful nodes – and remain unchanged throughout the network lifetime. Then, they define network lifetime as the time until the first cluster head fails (n-of-n cluster heads). This approach is very limited, as in most clustering schemes, cluster heads vary dynamically to reduce the load between homogeneous nodes. In addition, all the constraints from the discussion of n-of-n lifetime also apply here.

Finally, it is possible to define network lifetime as the time until all nodes have been drained of their energy. This metric is very rarely used, for example in [20], and then only as a "best-case" metric in combination with other metrics. This is of course due to the fact that the metric is far too optimistic to be useful. In most cases, a sensor network stops providing any useful service a long time before the last node finally fails.

In summary, it is evident that defining network lifetime solely based on the number of alive nodes is insufficient because neither the ability to communicate measurements nor the ability to sense events in the region of interest are incorporated into these metrics.

B. Network lifetime based on sensor coverage

Considering the specific characteristics of sensor networks, measuring the network lifetime as the time that the region of interest is covered by sensor nodes seems to be a natural way to define the lifetime. Coverage can be defined in different ways, depending on the composition of the region of interest and the achieved redundancy of the coverage. The region of interest can be a two-dimensional area or a three-dimensional volume where each point inside the area or volume has to be covered. This is often referred to as area or volume coverage. If only a finite set of target points inside an area has to be covered, the corresponding coverage problem is called target coverage. A third coverage problem, barrier coverage, describes the chance that that a mobile target can pass undetected through a barrier of sensor nodes [21].

There are two approaches to describe the degree of coverage redundancy that can be achieved by a given sensor network. The first approach requires that only a given percentage α of the region of interest is covered by at least one sensor. This is commonly called α-coverage. The second approach aims to achieve more redundancy and thus requires that each point within the region of interest is covered by at least k sensors. This is termed k-coverage.

Several papers base their definitions of network lifetime on a coverage variant. Among these, the most common definition uses 1-coverage to define the lifetime as the time that the region of interest is completely within the sensing range of at least one sensor node, i.e. the region is covered by at least one node. This definition is adopted for target coverage [22], [23] and for area coverage [24], [25], respectively.

A less strict variant of this definition is that only a fraction α of the region of interest needs to be covered. This definition can be found for example in [26]–[28]. A stricter variant demanding that each point is covered by at least k nodes is adopted for example in [29].

Sensor coverage is often argued to be the most important measure for the quality of service a sensor network provides. There is a lot of ongoing research concerning coverage in sensor networks, often in the context of deployment strategies or scheduling algorithms. Good surveys can be found for example in [21], [30]. However, defining network lifetime solely based on the achieved coverage is not sufficient for most application scenarios because it is not guaranteed that the measured data can ever be transmitted to a sink node.

C. Network lifetime based on connectivity

Another group of metrics takes the connectivity of the network into account. Connectivity is a metric that is commonly encountered in the context of ad hoc networks because there is no notion of sensor coverage in ad hoc networks and thus the ability to transmit data to a given destination is most important. The definition for ad hoc network lifetime given by Blough et al. [31] defines the lifetime as the minimum time when either the percentage of alive nodes or the size of the largest connected component of the network drop below a specified threshold. However, this definition only takes the size of the largest connected component in the network into account. This is clearly insufficient in sensor networks where connectivity towards a base station is what matters most. This is reflected in [32], where connectivity is defined as the percentage of nodes that have a path to the base station.

Baydere et al. [33] and Yu et al. [34] define the network lifetime in terms of the total number of packets that could be transmitted to the sink. While this number can serve as an indicator for the persistence of the network, it is very dependent on the actual algorithms used in the network. If, for example, data aggregation algorithms are used, the number of packets to be transmitted to the sink is being reduced. However, these aggregated packets contain the same degree of information as the much higher number of non-aggregated packets. Therefore, the applicability of this metric in comparing the lifetimes of different network setups is limited. Especially when data aggregation algorithms are employed, this metric loses much of its

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expressive power. Another drawback is that the number of transmitted messages gives no clue how long (in time units) the network was able to measure its environment. Even if the traffic pattern produced by the sensing application is known, no conclusions can be drawn about the absolute lifetime because the pattern can be modified by packet loss or data aggregation. Similar considerations hold for in-network data processing [9].

A third metric aiming at network connectivity defines the network lifetime in terms of the number of successful data gathering trips [35]. In [36] this is further confined to the number of trips possible "without any node running out of energy". This statement effectively reduces the definition to n-of-n lifetime, the difference being only that the lifetime is not given in time units, but in the number of data gathering trips. So, in addition to the drawbacks described for n-of-n lifetime, the drawbacks for the definition based on the total number of transmitted packets also apply.

Integrating connectivity in a network lifetime metric is certainly a good idea. However, it is important to consider connectivity towards a base station, not just connections between arbitrary sensor nodes. In addition, measuring the lifetime of a connected network in terms of numbers of transmitted packets is not comparable across different networks, and gives no indication of the absolute network lifetime.

D. Network lifetime based on sensor coverage and connectivity

Due to the described limitations, several authors combine the coverage-based metrics with connectivity metrics. The network lifetime metric as defined in [37], [38] gives the time when either the coverage or the connectivity drop below a predefined threshold. In this case, coverage is measured in terms of α-coverage as discussed before. Connectivity is measured in terms of the packet delivery ratio at the sink node.

Some authors completely hide details on their definition [21], [39], [40] and define network lifetime for example as "the time interval that the network can perform the sensing functions and transmit data to the sink" [21]. In other terms, network lifetime is defined to be the time until either coverage or connectivity are lost. The exact definition of coverage and connectivity is left unspecified. Mhatre et al. [39] do not measure the lifetime in traditional time units, but in the number of successful data gathering trips. The disadvantages of this approach have already been discussed above.

Another interesting analysis of network lifetime can be found in a paper by Mo et al. [29]. They define lifetime as the expectation of the interval during which the probability that connectivity and k-coverage are guaranteed is at least β. So far, there are no big differences to the other approaches in this section. However, in contrast to most other definitions, Mo et al. allow for the variation of sensing ranges between sensor nodes. This is an important characteristic, as it is not to be expected that the sensing ranges in real-world deployments have exactly the same size on all the nodes.

E. Network lifetime based on application quality of service requirements

A number of researchers define network lifetime solely in terms of the application quality of service requirements. We appreciate this approach, especially when considering the fact that every design decision in a sensor network completely depends on the specific application the network is designated to perform.

For example, Kumar et al. [41] state "We define the lifetime of a WSN to be the time period during which the network continuously satisfies the application requirement." Nevertheless, this definition illustrates the most important drawback of such a formulation; it is too abstract to be of any use in a practical studies of sensor networks. Although it covers every possible aspect by putting it all into the application requirements, the possible characteristics of application requirements are left unspecified.

Another definition in this domain is the time until "the network no longer provides an acceptable event detection ratio", as stated by Tian et al. [20]. Although this definition is also quite vague, it does specify one application requirement, namely that of a specified ratio of event detections. However, the detection of events does not necessarily include the transmission of a corresponding report to a sink node. The definition therefore lacks a characteristic that is important for most sensor networks.

F. Network lifetime as defined by Blough and Santi

One definition of sensor network lifetime, namely that of Blough and Santi [31], seems to provide a more concise meaning to the term than most others. They define the lifetime of a sensor network as the minimum of three points in time, each parameterizable with a constant ($0 \leq c_1, c_2, c_3 \leq 1$) to allow for flexible mappings of application requirements. The first time point t_1 indicates the loss of connectivity in the network. Formally, t_1 is the time it takes for the cardinality of the largest connected component of $G(t)$ to drop below $c_1 * n(t)$, where $G(t)$ is the communication graph of the network at time t and $n(t)$ is the number of alive nodes at time t. The second time point t_2 indicates how many nodes are still functional at time t, or more exactly, t_2 is the time it takes for $n(t)$ to drop below $c_2 * n(0)$. The third time point t_3 states the loss of α-coverage. t_3 is the time it takes for the volume covered to drop below $c_3 * l^d$, assuming a region of interest of the form $R = [0, l]^d$, with $d \in 1, 2, 3$.

So, in this definition, three aspects are combined to form one flexible measure of network lifetime: the number of alive nodes, connectivity, and coverage. Each of the three aspects can be left out by setting its corresponding parameter to zero.

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Unfortunately, the definition also has its limitations. The coverage aspect, although very flexible in allowing a volume to be covered (and not just a two-dimensional area), does not allow for the possibility of covering only a set of target points. While target coverage could be reduced to volume coverage (by defining the region of interest as the smallest volume that includes all points from the target set), this would mean that the network has to cover a lot of empty space between the target points that could be ignored otherwise. The connectivity aspect only defines connectivity within the largest connected component of the communication graph. This does not necessarily include the sink nodes. So, with this definition of connectivity, the sink nodes could be oblivious to the events measured in the network after only a small number of nodes near the sink have failed and the remaining network still forms a large enough connected component. Finally, the definition includes no notion of mobility in the network. This can seriously affect the lifetime of a network and the evaluation of the network lifetime in a performance metric. All issues concerning mobility are discussed in more detail in the next section.

G. Summary

In summary, we provide a list of the discussed network lifetime definitions, each with a short outline of the definition and selected references that use or propose this definition in the literature.

1) the time until the *first sensor is drained of its energy* [11]–[13], [15], [36], [42]–[44]
2) the time until the *first cluster head is drained of its energy* [18], [19]
3) the time there is at least a *certain fraction β of surviving nodes* in the network [16], [17], [42], [45]–[47]
4) the time until *all nodes have been drained of their energy* [20]
5) *k-coverage*: the time the area of interest is covered by at least k nodes [29]
6) *100% coverage*
   a) the time *each target* is covered by at least one node [22], [23]
   b) the time *the whole area* is covered by at least one node [24], [25]
7) *α-coverage*
   a) the *accumulated time* during which *at least α portion of the region is covered* by at least one node [28], [48], [49]
   b) the time until the *coverage drops below a predefined threshold* α (*until last drop below threshold*) [26], [27]
   c) the continuous operational time of the system *before either the coverage or delivery ratio first drops* below a predefined threshold [32], [37], [38]
8) the number of *successful data gathering trips* [35], [36], [39]
9) the number of *total transmitted messages* [33], [34]
10) the percentage of nodes that have a *path to the base station* [32]
11) the expectation of the entire interval during which the probability of guaranteeing *connectivity and k-coverage* simultaneously is at least α [29]
12) the time until *"connectivity" or "coverage" are lost* [21], [39], [40], [50]
13) the time until the *network no longer provides an acceptable event detection ratio* [20]
14) the time period during which the *network continuously satisfies the application requirement* [31], [41], [46], [47]
15) min(t1, t2, t3) with t1: time for cardinality of largest connected component of communication graph to drop below $c1 * n(t)$, t2: time for n(t) to drop below $c2 * n$, t3: time for the covered volume to drop below $c3 * l^d$ [31]

III. Open Issues and General Requirements

None of the discussed definitions of network lifetime reflects all the application demands and the environmental influences. Typically, the real network lifetime is approximated under a set of very specific conditions. Therefore, the existing definitions are not applicable in a general context but in networks that meet the specified conditions. However, there are many more parameters influencing sensor network lifetime than just the aspects included in existing definitions.

A. Node mobility and topology changes

At the moment, most authors only consider networks with stationary sensor nodes. Some consider mobility as a chance for improving network functionality. Others also state that large-scale mobility complicates matters a lot. This indicates that mobility is indeed a very controversial subject in sensor networks. It offers chances as well as risks for the functionality of the network. However, whether chances or risks prevail, it should be clear that it is important to take mobility into account even in a stationary network.

The first reason we can give for this is that mobility can be simply regarded as a series of topology changes. With the movement of a node, some network links can break, others can be established, and the covered area may be altered. In turn, every topology change can be seen as a special case of "mobility". Considering for example node failures, some network links break when a node fails, and the area covered by sensors is altered in some way. The effects are nearly the same as with traditional mobility, i.e. node movements. So, even if the nodes themselves have no possibility for moving on their own, the network should be expected to be able to cope with node failures.

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Another reason is that in every real-world deployment, there is an environment that affects the network in some way. Sensor nodes may roll down a hill or be moved – whether on purpose or accidentally – by external forces, e.g. by animals kicking at them. These two examples (node failure and accidental mobility) demonstrate that mobility, i.e. topology changes, can occur even in a stationary network. A network that cannot cope with mobility at all will probably face a very short lifetime – and a definition of network lifetime that does not explicitly account for mobility at all will probably create wrong lifetime estimations.

The fact that node mobility and topology changes can complicate the analysis of network lifetime has already been mentioned by Blough and Santi [31]. Consider one of the abstract definitions of lifetime described above, the definition by Kumar that measures lifetime as the time period during which the network continuously satisfies the application requirement. For example, what is the network lifetime if the network is considered alive from a starting time t_0 until time t_1, not alive until time t_2, alive again until time t_3, and not alive after that? Is it the time until t_1? Is it the sum of all the time periods during which the network is alive, i.e. the sum of $t_1 - t_0$ and $t_3 - t_2$? Or is it the time until t_3? Blough and Santi do not provide a solution for this question. We address this issue in section V.

In the literature, several approaches have been discussed to improve the network behavior using mobility. Several authors investigate the improvement of sensor coverage over time by exploiting node mobility, e.g. if there are not enough static nodes to cover the region of interest [51]–[55]. Others claim that mobile nodes can improve network connectivity by carrying data from one part of the network to another [12], [45]. The influence of mobility on clustering algorithms is surveyed in [56]. The effects on networks with mobile sinks or mobile relays are studied for example in [12], [57], [58]. Even combined effects have been studied such as the optimization of coverage and network lifetime using virtual movements, e.g. dynamic node re-programming [59].

B. *Heterogeneity*

About one third of the papers reviewed for this survey do not state whether they consider homogeneous or heterogeneous nodes. While it is probably safe to assume that the authors are exploring homogeneous networks in these cases, it shows that the current level of awareness for node heterogeneity leaves a lot of room for improvement. Most of the authors dealing with heterogeneous nodes concentrate on just one type of heterogeneity. However, a short literature study revealed at least eight to ten types of heterogeneity that could have a significant impact on the functionality and lifetime of sensor networks.

The most common type of heterogeneity found in the literature today classifies the nodes in the network in two categories depending on their battery power. Most of the nodes are assumed to have a regular amount of energy, while a few nodes have a significantly larger energy reservoir at their disposal (or even unlimited energy). This type is mentioned for example in [15], [17], [19], [23], [39], [42], [43]. Many authors consider this in the context of clustering schemes, where the more powerful nodes are assumed to permanently perform the role of cluster heads. An important observation in this context is that nodes can become heterogeneous in terms of battery power simply because of differences in the discharge behavior of their batteries (depending on environmental factors, for example temperature differences in the region of the deployment).

Another variant is to presume that some nodes have to send a larger amount of data than others, for example because of different sensor types, as mentioned in [17], [60]. If the amount of data is the only criterion of interest, this type can be mapped to heterogeneity in the available battery power discussed above.

However, if sensing coverage is of any importance, the different sensor types have to be considered explicitly because the coverage requirements have to be fulfilled by each type of sensor. Nodes with different types of sensors are considered in [61]. In [28], [29], [43], [62], the authors consider nodes with varying sensing ranges (either due to the sensor characteristics, i.e. different sensor types, or due to environmental variations).

Powerful nodes with higher processing power and memory capacity are considered by Lee et al. [43] and Soro et al. [19]. In both cases, also different energy levels are considered. This is reasonable as more powerful nodes (in terms of processing and memory) will usually be used as permanent routers or data aggregators. In this case, it is obvious to provide more powerful batteries as well.

Varying transmission ranges are considered in [15], [38], [63]. Mhatre et al. [15] assume that some nodes (the cluster heads) will be capable of long-range transmissions reaching the base station in a single hop. In contrast, Xing et al. [38] consider homogeneous nodes where the transmission ranges can vary and take irregular shapes due to environmental conditions. Zhou et al. [63] take a similar approach and develop models to treat radio irregularity. They also consider varying transmission powers (resulting, of course, in varying transmission ranges) as a type of heterogeneity.

Sometimes, mobility is classified as a kind of heterogeneity as well. We already discussed mobility issues in the last section.

Taking into account all these different sources of heterogeneity in a sensor network, it should be obvious why it is important to consider heterogeneity for the analysis of network lifetime. Heterogeneous nodes can have an influence on network lifetime in many ways. For example, the lifetime could be prolonged by the network backbone that is provided by the more powerful nodes in the network. Of course, the lifetime could also be shortened if some nodes gather a lot more data than others and then fail earlier due to necessary radio activity. Heterogeneity can also have an influence on the applicability of algorithms, especially of clustering schemes.

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C. Application characteristics

The application is the driving force of any sensor network. However, it is useful to distinguish between the overall application that a sensor network is made for (like monitoring environmental parameters in a building), and the programs running on each single sensor node. For example, it might benefit the overall application to split its duties into several tasks that are performed by different nodes. This leads to a heterogeneity of tasks in a network. Consider, for example, a number of nodes sensing temperature values and sending them to a local destination. In this example, the local destination is just another node aggregating the data and for further forwarding to the base station. This approach is especially useful if the individual nodes have not enough resources to perform both tasks simultaneously. In that case, the lifetime of the network strongly depends on the network's ability to provide an adequate distribution of all necessary tasks over all available sensor nodes [10], [64].

The destination for data packets that is used by the individual sensor nodes can affect communication patterns in the network. In addition to the simple cases with single fixed destinations either in the middle or at the edge of the network, multiple destinations at different places or even mobile sinks need to be considered as well. All variants potentially lead to different communication patterns in different regions of the network, thus influencing energy consumption. This effect has been studied for example in [65].

The final and possibly most important factor influencing network lifetime at the application level is the node activity in terms of sensor measurements, data processing, and communication [3]. In all cases, the activity can be triggered by events (for example, sending of data because sensor measurements exceed some threshold), it can be carried out in regular intervals, or it can be initiated by a request from another node. The frequency of energy-consuming actions will probably be quite different in the three cases.

D. Quality of service

It has already been stated above that the application is the driving force of every sensor network. It is to be expected that each application has different demands on the required services in the network and their quality of service parameters. Obviously, a definition of network lifetime should take the QoS requirements of the application into account. Consequently, this leads to the central question what the most common application requirements in sensor networks are. While the quality of service parameters for traditional networks have been thoroughly studied, there has been relatively few work on this topic in the context of sensor networks, e.g. [60], [66].

Traditional QoS measures include the delay (the response time and its components: transmission times, propagation delays, processing times, queuing delays, idle times), the jitter (the delay variation), the throughput and bandwidth, the loss and error rates (packet errors, bit errors), the resource consumption (processing, memory, bandwidth, power), the reliability (MTTF: mean time to first failure) and availability (downtime), and the overall costs (total cost of ownership, return on investment). The QoS requirements of sensor networks can be different from these traditional measures. End-to-end QoS measures are not as important as "collective" parameters. For example, Chen et al. [66] state, "collective latency is defined as the difference between the time at which the first packet related to this event is generated by the source sensors and the time at which the last packet related to this event or the last packet used to make a decision arrives at the sink".

Examples for additional QoS measures being cited as important for sensor networks are the coverage, event detection ratio and exposure (often stated as the main QoS parameters for sensor networks), connectivity (availability, latency, loss), requirements on a continuous service (service disruptions up to a length of n are tolerated, indicates "mission-criticality"), the observation accuracy (measurement errors), and the optimum number of sensors sending information toward information-collecting sinks [60], [66], [67]. Obviously, many parameters already appeared in the lifetime discussion. We see a deep relation between lifetime and quality of service in sensor networks. Therefore, we will integrate QoS directly in our lifetime definition.

E. Completeness

Most of the existing lifetime definitions fail to consider multiple important aspects in sensor networks in a single step. For example, connectivity and coverage are often investigated independently whereas these measures essentially influence each other. In general, we also agree on the advantage of analyzing specific application demands independently for a better understanding of the particular effects. Nevertheless, if different definitions are used that cannot be brought together in a final evaluation step, results become incomparable. This is a serious problem in sensor network research. Although it could be tempting to formulate a new definition of lifetime for each new network, this would certainly be less flexible and less comparable than a single definition incorporating many common application requirements.

To summarize this section, we provide a short overview of the most important requirements in each category in table I, together with some pointers to the literature.

IV. Modeling single sensor nodes

Network lifetime is a metric that depends on the lifetimes of the single nodes that constitute the network. This fact does not depend on how the network lifetime is defined. Each definition can finally be reduced to the question when the individual

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Mobility	• complicates analysis of network lifetime [31] • improves sensor coverage [51]–[54] • improves network connectivity [12], [45] • influences clustering [56] • mobile sinks or mobile relays [12], [57], [58] • combined effects [59]
Heterogeneity	• Some nodes have more battery power [15], [17], [19], [39], [42], [43], [53] • The amount of data each node must communicate varies [17], [60] • Nodes may have different types of sensors [61] • Sensing radius is variable / some nodes have larger sensing radii [28], [29], [43], [62] • Some nodes have higher processing power and memory capacity [19], [43] • Some nodes have longer transmission ranges / transmission range is variable [15], [38] • The transmission power varies [63]
Application characteristics	• distribution of sub-tasks • destination for data packets • node activity (sensing, processing, communication): by event, by request, regular intervals [68]
Quality of service	• general issues [60], [67] • collective QoS parameters [66] • coverage • exposure • connectivity • requirement of continuous service • observation accuracy • optimum number of sensors
Completeness	• interdependent measures • results not comparable because of incompatible lifetime definitions

TABLE I
REQUIREMENTS SUMMARY

nodes fail. Thus, if the single node lifetimes are not predicted accurately, it is possible that the derived network lifetime metric deviates in an uncontrollable manner. It should therefore be clear that an accurate and consistent modeling of the single nodes' lifetimes is very important. However, a detailed discussion of all the different approaches found in the literature is beyond the scope of this paper. In consequence, we will only give a short overview of the most important points to be considered.

The lifetime of a sensor node depends basically on two factors: how much energy it consumes over time, and how much energy is available for its use. Following the discussion by Akyildiz et al. [68], the predominant amount of energy is consumed by a sensor node during sensing, communication, and data processing activities. The amount of energy available to a sensor node also depends on the capacity of its battery, how this capacity is used, and the use of energy scavenging techniques.

A. Sensing

The amount of energy consumed by the sensing hardware depends on the types of sensors and the frequency and duration of the sensor measurements. Detailed measurements of the current draws of sensing hardware are presented for example by Shnayder et al. [69]. In this work, the authors measured the current draws of the components of a Mica2 sensor node, including the sensor board available for Mica2 nodes.

However, Raghunathan et al. [70] state that due to the diversity of available sensor types, a typical power consumption number does not exist. They classify sensor types as passive and active sensors. Passive sensors, including temperature or seismic sensors, consume a negligible amount of power compared to other node components. In contrast, active sensors (like sonar rangers or repositionable cameras) can require significant amounts of energy. It is therefore very difficult to estimate the power consumption of the sensors on a node without knowing the types of sensors and their usage pattern by the node application. This is one possible reason that many authors do not consider the power consumed by the sensors at all. However, a number of authors infer the sensor power consumption by assuming a constant consumption per sensed bit together with a fixed sensing rate [25]. This can be a good approximation if the parameters are chosen adequately.

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B. *Communication*

It is generally agreed that sensor nodes spend most of their energy on communication. This is also supported by measurements, for example those in [70]. A logical consequence is that many authors focus only on the energy spent on communication when designing energy efficient algorithms for sensor networks. However, an important point is that the radio modules available today consume nearly the same amount of energy for idle listening as for receptions or transmissions of data packets. Albeit often neglected in lifetime studies, this fact has also given rise to a lot of work on algorithms for determining good or near-optimal sleep schedules for sensor nodes. Wang et al. [71] give a good overview over this field of study.

C. *Data processing*

Some authors, for example [70], [72], state that the energy consumed by a sensor node for transmitting one bit of information is approximately equal to the energy consumed by executing up to 1000 processor instructions. This indicates that computation should be preferred over communication, for example to employ data aggregation or compression algorithms before transmitting the data. However, recent measurements presented in [73] show that for example cryptographic hash and encryption algorithms can take a long time to complete. For example, hashing one kByte of data with SHA-1 takes about 130 ms on a typical sensor node, while encrypting the same amount of data takes more than 1.6 s. The effects of such long-running computations are twofold: first, the energy consumed by such operations is not negligible, and second, the duration of the operations essentially contributes to the latencies of the data messages.

D. *Battery performance*

The performance of sensor node batteries can be enhanced if several technical battery issues (such as the charge recovery effect, also called relaxation effect, or the rated capacity effect) are taken into account in all energy-consuming operations, especially in communications. Chiasserini et al. [74] give a good overview of the physical characteristics of common batteries, and they also derive a traffic shaping algorithm that exploits the charge recovery effect.

Welsh et al. [61] propose a number of other techniques to improve node lifetimes by tweaking battery usage. One is to employ batteries with higher energy densities. However, as these batteries are more expensive than traditional battery types, the nodes would become more expensive. Another approach is the use of battery-less technology which exploits, for example, the piezoelectric effect. The last technique mentioned by Welsh et al. is to combine rechargeable batteries with energy scavenging.

E. *Energy scavenging*

Rabaey et al. [75] give a comparison of several possible sources for energy scavenging, including solar, vibrations, and acoustic noise, and compare them with nuclear reactions and traditional battery types. Roundy et al. [76] focus on vibrations and study the problems associated with this type of energy source in detail. There is a lot of ongoing research on energy scavenging methods, mostly in the field of electrical engineering. However, further study of these approaches is beyond the scope of this paper.

V. A MORE CONCISE DEFINITION

Based on the survey of lifetime definitions and the corresponding discussion of open issues, we now formulate our own definition in this section. The overall objective is to develop a definition that can be parameterized according to the application requirements but that also provides comparability between different optimization efforts of algorithms and methods in WSN.

A. *Prerequisites*

The region of deployment is described by R. There can be different definitions for R while the concrete specification is not relevant for the definition of network lifetime. Some possibilities include a rectangle ($R = [0, a_1] \times [0, a_2], |R| = a_1 * a_2$), a cuboid ($R = [0, d_n]^n, |R| = \prod d_n$), or a circle ($|R| = \pi r^2$).

Each sensor node can be equipped with one or more different sensors. Therefore, we define the set of sensor types present in a network as $Y = \{y_1, \ldots, y_k\}$. The set of all existing sensor nodes is then called S^Y. The types of sensors available on each of the nodes is represented by the subsets $Y_i \subset Y$. It is important to note that each sensor node is associated to a *subset* of the set of sensor types. This means that there may be more than one sensor on a node, and there may also be zero sensors on a node. The total number of available sensor nodes is n.

$$S^Y = \left\{ s_1^{Y_1}, \ldots, s_n^{Y_n} \right\}, \; Y_i \subset Y \tag{1}$$

$$|S^Y| = n \tag{2}$$

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Starting from the set of all sensor nodes S^Y, we define the set of all nodes that are alive at a certain time t as $U(t)$. In equation 3, $u_i^{Y_i}$ is a sensor node from the set of all sensor nodes (defined above), which is equipped with the sensor types denoted by the subset Y_i, and whose energy is not yet depleted.

$$U(t) = \left\{u_1^{Y_1}, \ldots, u_m^{Y_m} \mid u_m^{Y_m} \text{ alive}\right\}, U(t) \subset S^Y, |U(t)| = u(t) \tag{3}$$

Now we can define the set of nodes that are active at a time t as $V(t)$. For a node to be active, it has to be alive (therefore $V(t)$ is a subset of $U(t)$), and it must not be in a sleep state.

$$V(t) = \left\{v_1^{Y_1}, \ldots, v_l^{Y_l} \mid v_i^{Y_i} \text{ active}\right\}, V(t) \subset U(t), |V(t)| = v(t) \tag{4}$$

The set of sink nodes or base stations $B(t)$ is defined to be a subset of the existing nodes S^Y. In some network settings, sink nodes might be ordinary sensor nodes acting as base stations for other nodes. For this reason, the definition retains the possibility for sink nodes to fail or sleep just like any other node. The set of sink nodes may vary over time, and it is also possible that there are no sink nodes present in the network at some point in time.

$$B(t) = \{b_1, \ldots, b_k\} \subset S^Y \tag{5}$$

The communication graph of the network at a time t is given as the undirected graph $G(t) = (V(t), E(t))$. This definition assumes that communication between two nodes is always possible in both directions. Apart from that, no assumptions are made about the communication ranges of the nodes. Note that only active nodes from the set $V(t)$ are included in the communication graph. In order to express the ability of two arbitrary nodes m_i and m_j to communicate at a time t, it is necessary to check if there exists a series of edges in $G(t)$ starting at m_i and ending at m_j. To express this formally, we renumber node m_i as m_1, node m_j as m_n, and all nodes on the path between the two nodes accordingly. The ability of nodes m_1 and m_n to communicate at a time t can then be expressed as $\kappa(t, m_1, m_n)$. The number of hops needed for the communication is $n-1$.

$$\kappa(t, m_1, m_n) \equiv \begin{cases} \forall i \in \{1, \ldots, n-1\} \ : m_i \in V(t) \wedge (m_i, m_{i+1}) \in E(t) & m_1 \neq m_n \\ 1 & m_1 = m_n \end{cases} \tag{6}$$

The set of target points to be sensed by the network can be defined as $P^Y(t)$. Each target point can be sensed only by a certain collection of sensor types, denoted by the subsets $Y_i \subset Y$. It is possible that a target can be sensed by multiple sensor types. However, it is probably not very useful to have targets that cannot be sensed by any kind of sensor. Therefore, we require that Y_i is not the empty set in this equation. Target points outside the region of deployment R are not allowed.

$$P^Y = \left\{p_1^{Y_1}, \ldots, p_m^{Y_m} | p_i^{Y_i} \in R \wedge Y_i \subset Y \wedge Y_i \neq \emptyset\right\} \tag{7}$$

We define the area (or volume) that is covered by all sensors of a certain type y at a time t as $A^y(t)$. In this equation, $A_{v_i}^y$ denotes the area that is covered by the sensor of type y of node v_i. The shape of this area can be any shape representing the sensing range of a sensor. This could be, for example, a circle centered at v_i or a circle section originating at v_i.

$$A^y(t) = \bigcup_{\forall v_i \in V(t)} A_{v_i}^y \cap R, y \in Y \tag{8}$$

We are now ready to define a series of criteria that may influence network lifetime at least in some network settings. Each criterion can be excluded from the final definition of lifetime by setting its modification factor correspondingly. In the following equations, these parameters are denoted by c_{**}.

B. Area coverage for single sensor types

Area coverage is a family of criteria, one for each type of sensor. The requirement is that the area covered by all sensors of type y must be greater than a certain portion of the deployment region. In other words, the fraction of the deployment region covered by type-y-sensors $A^y(t)/|R|$ must be greater than the parameter c_{ac}^y. This parameter may vary depending on the sensor type.

$$\zeta_{ac}^y(t) \equiv \ A^y(t) \geq c_{ac}^y * |R|, y \in Y \tag{9}$$

C. Target coverage for single sensor types

The target coverage criterion requires that for each type of sensor y a certain portion of all targets, which can be sensed by type-y-sensors, must be within the area covered by those sensors. The set of targets that can be sensed by type-y-sensors is a subset of P^Y and denoted as P^y. In this definition, it is not relevant if the targets are stationary or mobile. At each point in time, the current position of the targets is evaluated. Between the evaluations, the target positions may be updated.

$$\zeta_{tc}^y(t) \equiv \ \exists P_m^y \subset P^y \wedge |P_m^y| \geq c_{tc}^y * |P^y| \wedge P_m^y \in A^y(t), y \in Y \tag{10}$$

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D. k-coverage for single sensor types

The k-coverage criterion requires that each point in the region of interest has to be within the sensing range of at least k active sensors. The k-coverage parameter c_k^y indicates the magnitude of k. The function τ returns 1 if a certain point x is withing the sensing radius of the type-y-sensor of node v. The function σ indicates by how many active sensors a point x is covered.

$$\tau(x, v^y) = \begin{cases} 1 & x \in A_v^y \\ 0 & x \notin A_v^y \end{cases}$$

$$\sigma(t, x) = \sum_{i=0}^{v(t)} \tau(x, v_i^y)$$

The k-coverage criterion is fulfilled if σ is not smaller than the k-coverage parameter c_k^y for all points in the region of interest. There are two variants depending on the kind of the region of interest: one for an area (equation 11) or volume, and one for targets (equation 12).

$$\zeta_k^y(t) \equiv \forall x \in R: \ \sigma(t, x) \geq c_k^y \tag{11}$$
$$\zeta_k^y(t) \equiv \forall p \in P: \ \sigma(t, p) \geq c_k^y \tag{12}$$

E. Number of active nodes

At least a portion of c_{an} times the number of existing nodes must be active at any time (sleeping nodes are not considered active).

$$\zeta_{an}(t) \equiv v(t) \geq c_{an} * n \tag{13}$$

F. Number of alive nodes

The portion of alive nodes, including sleeping nodes, must be greater than c_{ln} times the number of existing nodes at any time. This means that the parameter c_{ln} can never be truly switched off because the true greater relation ensures that the lifetime of the sensor network is constrained to be at most the time of the failure of the last alive node. This has already been discussed as the *best case* for sensor network lifetime in the related work section.

$$\zeta_{ln}(t) \equiv u(t) > c_{ln} * n \tag{14}$$

G. Availability (service disruption tolerance)

A service disruption of at most c_{sd} seconds is tolerated. This parameter is included in the final lifetime definitions (equations 29 - 32).

H. Latency

For each type of packet in the network, all packets of the type must arrive at a sink node within a period of c_{la} after the initial sending.

$$\zeta_{la} \equiv \forall \text{packets} : \text{packet latency} \leq c_{la} \tag{15}$$

I. Loss and error

At most a portion of c_{lo} packets of all data packets sent in the network may be lost or unusable due to packet loss or error. This is equivalent to demanding that at least a portion of $1 - c_{lo}$ packets must be correctly received by a sink node, i.e that the packet delivery ratio must be at least $1 - c_{lo}$.

$$\zeta_{lo} \equiv \frac{\text{lost packets} + \text{erroneous packets}}{\text{total packets}} < c_{lo} \tag{16}$$

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J. Connectivity

In basically all sensor networks, traffic flows from the individual sensor nodes towards one or more sink nodes. It is therefore not important to ensure connectivity between all sensor nodes, but rather to ensure connectivity towards the sink nodes. The function $\chi(v_j, t)$ indicates if a node v_j has a connection to any active sink node in $B(t)$ at the time t. If there is no active sink node, the indicator function returns false because a connection to a sink node does not exist.

$$\chi(v_j, t) \equiv \exists b_i \in B(t) \wedge (v_j, b_i) \in V(t) \wedge \kappa(t, v_j, b_i) \tag{17}$$

One criterion to evaluate connectivity in a sensor network is to require that at least a certain portion of all active nodes have a connection to a base station.

$$\zeta_c(t) \equiv \exists V_c \subset V(t) : |V_c| \geq c_c * |V(t)| \wedge \forall v_c \in V_c : \chi(v_c, t) \tag{18}$$

Another criterion for connectivity is to include the coverage criteria in the definition. This is a different constraint than connectivity and coverage on their own, because the nodes covering the area could be different from those able to communicate. This has already been mentioned by Thai et al. [77].

For the connected coverage criteria it is useful to redefine the covered area $A^y(t)$ as $A^y_*(t)$. The difference between the two definitions is that $A^y(t)$ uses all active nodes, whereas $A^y_*(t)$ uses only those active nodes with a path to the sink.

$$A^y_*(t) = \bigcup_{\forall v_i \in V(t) : \chi(v_i, t)} A^y_{v_i} \cap R \tag{19}$$

Based on $A^y_*(t)$ and the previous definitions of area and target coverage in sections V-B and V-C, we can now define the criteria for connected area coverage $\zeta^y_{cac}(t)$ and connected target coverage $\zeta^y_{ctc}(t)$. Both criteria are defined for a specific sensor type y, therefore resulting in a family of criteria for all the sensor types. For area coverage, the area covered by those active sensor nodes with a path to a sink must be greater than a specified portion of the whole area.

$$\zeta^y_{cac}(t) \equiv \; A^y_*(t) \geq c^y_{cac} * |R|, y \in Y \tag{20}$$

For target coverage, the portion of targets covered by active sensor nodes with a path to a base station has to be at least a specified percentage of all targets.

$$\zeta^y_{ctc}(t) \equiv \; \exists P_m \subset P \wedge |P_m| \geq c^y_{ctc} * |P| \wedge P_m \in A^y_*(t), y \in Y \tag{21}$$

K. Global coverage criteria

The coverage criteria defined so far include area coverage, target coverage, k-coverage, connected area coverage and connected target coverage. However, each of these coverage criteria has only been defined for one type of sensor. Therefore, they have to be aggregated to cover all sensor types available in a network to indicate if the coverage criteria are fulfilled for each sensor type. This is done in the following equations. As can be seen, a global coverage criterion is only taken to be satisfied if the conjunctive combination of all single node criteria is fulfilled.

global area coverage: $$\zeta_{ac}(t) = \bigwedge_{\forall y \in Y} \zeta^y_{ac}(t) \tag{22}$$

global target coverage: $$\zeta_{tc}(t) = \bigwedge_{\forall y \in Y} \zeta^y_{tc}(t) \tag{23}$$

global k-coverage: $$\zeta_{k}(t) = \bigwedge_{\forall y \in Y} \zeta^y_{k}(t) \tag{24}$$

global connected area coverage: $$\zeta_{cac}(t) = \bigwedge_{\forall y \in Y} \zeta^y_{cac}(t) \tag{25}$$

global connected target coverage: $$\zeta_{ctc}(t) = \bigwedge_{\forall y \in Y} \zeta^y_{ctc}(t) \tag{26}$$

L. Definition of network lifetime

We can now begin to integrate the presented definitions of single criteria into our final definition of network lifetime. First, we define an aggregate criterion, the liveliness of the network $\zeta(t)$ as the conjunctive combination of all single criteria. Table II gives an overview of the parameters used in the criteria definitions, their ranges and which values can be used to turn each criterion off.

$$\zeta(t) \equiv \zeta_{ac}(t) \wedge \zeta_{tc}(t) \wedge \zeta_k(t) \wedge \zeta_{an}(t) \wedge \zeta_{ln}(t) \wedge \zeta_{la} \wedge \zeta_{lo} \wedge \zeta_c(t) \wedge \zeta_{cac}(t) \wedge \zeta_{ctc}(t) \tag{27}$$

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parameter	meaning	range	off
c_{ac}^y	area coverage	$[0,1]$	0
c_{tc}^y	target coverage	$[0,1]$	0
c_k^y	k-coverage	$[0,\infty]$	0
c_{an}	portion of active nodes	$[0,1]$	0
c_{ln}	portion of alive nodes	$[0,1]$	0
c_{sd}	service disruption tolerance	$[0,\infty]$	∞
c_{la}	maximum tolerable latency	$[0,\infty]$	∞
c_{lo}	maximum portion of packet loss or error	$[0,1]$	1
c_c	portion of nodes with path to a sink	$[0,1]$	0
c_{cac}^y	connected area coverage	$[0,1]$	0
c_{ctc}^y	connected target coverage	$[0,1]$	0

TABLE II
PARAMETERS

We then define T to be the ordered sequence of all points in time where the aggregate criterion $\zeta(t)$ changes its value (from *true* to *false* or vice versa). We do this by checking ζ at time t and at time $t-\epsilon$, i.e. just before time t.

$$T = \{t_i | (\zeta(t_i-\epsilon) \wedge \neg\zeta(t_i)) \vee (\neg\zeta(t_i-\epsilon) \wedge \zeta(t_i))\}, t_i < t_{i+1}, i \in \mathbb{N}_0 \tag{28}$$

To clarify the following definitions, we define e to be the minimal index in T after which a service disruption of more than c_{sd} seconds follows. If such an index does not exist (for example if the service disruption tolerance is infinite), e is taken to be the last index in T, i.e. $|T|$.

$$e = \begin{cases} \min(i \in [0,|T|-1] : \neg\zeta(t_i) \wedge (t_{i+1}-t_i) > c_{sd}) & \text{if such } i \text{ exists} \\ |T| & \text{otherwise} \end{cases} \tag{29}$$

For further simplification, we define the periods of time during which the network is lively as t_i^a.

$$\forall i \in [0,e] : t_i^a = \begin{cases} t_{i+1}-t_i & \text{if } \zeta(t_i) \\ 0 & \text{otherwise} \end{cases} \tag{30}$$

We now propose two network lifetime metrics, both building on the previous definitions. Both metrics depict the network lifetime in seconds. The metrics probably become most expressive when used together.

The first metric gives the *accumulated network lifetime* Z_a as the sum of all times that $\zeta(t)$ is fulfilled (these are exactly the intervals t_i^a defined above), stopping only when the criterion is not fulfilled for longer than c_{sd} seconds.

$$Z_a = \sum_{i=0}^{e} t_i^a \tag{31}$$

The second metric, the *total network lifetime* Z_t, gives the first point in time when the liveliness criterion is lost for a longer period than the service disruption tolerance c_{sd}.

$$Z_t = t_e \tag{32}$$

VI. APPLICABILITY OF THE DEFINITION

A. *Mapping of existing definitions*

Nearly all definitions of network lifetime existing in the literature can be represented with our definition. In table IV, we provide parameter settings that reproduce the most common definitions described in the related work section. As can be seen, most of the criteria we employ in our lifetime definition have already been used in the literature – while not in such a comprehensive way. Other parts such as the ζ_{an} criterion (representing the number of active nodes), ζ_{la} (depicting the end-to-end latency of communications), and the tuple ζ_{cac} and ζ_{ctc} (representing the area and target coverage, respectively, under connectivity constraints) have been introduced to complete the definition according to the specific requirements in sensor networks.

However, some of the definitions of network lifetime discussed in section II can not be represented easily in terms of our new definition. This is not due to inattention towards these definitions, but due to several other reasons which we will explain now.

The definition targeting the failure of the first cluster head is not representable because there is no explicit notion of cluster heads in our definition. However, as cluster heads are mostly responsible for maintaining the connectivity to the base stations, this metric can be re-formulated in terms of one of the connectivity metrics in our definition.

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$A^y(t)$	area covered by y-sensors at time t
$A^y_*(t)$	area covered by y-sensors with path to sink at time t
$B(t)$	set of base stations
$\chi(v,t)$	indicates if v has a connection to a base station at time t
e	minimal index in T before service disruption follows
$E(t)$	edges in communication graph at time t
$G(t) = (V(t), E(t))$	communication graph at time t
$\kappa(t, m_1, m_n)$	nodes m_1 and m_n can communicate at time t
$n = \lvert S^Y \rvert$	number of existing sensor nodes
P^Y	set of target points
R	region of deployment
$\sigma(t,x)$	indicates by how many sensors x is covered at time t
S^Y	set of all existing sensor nodes
$\tau(x,v)$	indicates if x is covered by v
T	sequence of points in time where liveliness criterion changes
$U(t)$	set of nodes alive at time t
$V(t)$	set of nodes active at time t
$Y = \{y_1, \ldots, y_k\}$	set of sensor types present
$\zeta^y_{**}(t)$	indicates if liveliness criterion ** is fulfilled at time t for sensor type y
$\zeta_{**}(t)$	indicates if liveliness criterion ** is fulfilled at time t
$\zeta(t)$	indicates if the network is considered alive at time t
Z_a	accumulated network lifetime
Z_t	total network lifetime

TABLE III

SYMBOLS USED IN THE LIFETIME DEFINITION

lifetime definition	c^y_{ac}	c^y_{tc}	c^y_k	c_{an}	c_{ln}	c_{sd}	c_{la}	c_{lo}	c_c	c^y_{cac}	c^y_{ctc}
n-of-n lifetime	0	0	0	0	$\mathbf{1}$	∞	∞	1	0	0	0
k-of-n lifetime	0	0	0	0	$\mathbf{\frac{k}{n}}$	∞	∞	1	0	0	0
last node failure	0	0	0	0	$\mathbf{n}$	∞	∞	1	0	0	0
100% target coverage	0	$\mathbf{1}$	0	0	0	∞	∞	1	0	0	0
100% area coverage	$\mathbf{1}$	0	0	0	0	∞	∞	1	0	0	0
accumulated α-coverage	α	0	0	0	0	$\mathbf{n}$	∞	1	0	0	0
α-coverage (last drop)	α	0	0	0	0	∞	∞	1	0	0	0
α-coverage (first drop)	α	0	0	0	0	$\mathbf{0}$	∞	1	0	0	0
k-coverage	0	0	$\mathbf{k}$	0	0	∞	∞	1	0	0	0
packet delivery ratio β and α-coverage	α	0	0	0	0	∞	∞	$\mathbf{1}-\beta$	0	0	0
connectivity and k-coverage	0	0	$\mathbf{k}$	0	0	∞	∞	1	$v(t)$	0	0
Blough and Santi	$\mathbf{c_3}$	0	0	0	$\mathbf{c_2}$	∞	∞	1	0	0	0

TABLE IV

MAPPING

The definition of Blough and Santi [31] is represented in the last line of table IV. However, this representation is only partial, as their connectivity metric ”largest connected component” is missing. This is intentional because that metric does not incorporate application specific requirements such as the need for a particular base station. It should be replaced by a connectivity metric representing connectivity to a sink node.

The definitions measuring the lifetime in terms of the total number of packets arrived at the sink or the number of successful data gathering trips are not representable. This is because they do not give the lifetime in terms of a comparable time unit, but in terms of a number that can vary greatly depending on the algorithms employed. This has already been discussed earlier in this paper.

The remaining definitions can in principle be represented in terms of our definition, but are given too vaguely to derive precise numbers for their parameter settings. These definitions include the one targeting *connectivity* and *coverage*. We provide metrics for both connectivity and coverage, but as the authors did not specify the details, there is a broad range of possible representations for this definition. The definition based on the event detection ratio can be mapped entirely to coverage and connectivity criteria. Finally, the definitions targeting the application requirements are too abstract to find a specific representation.

B. Scenario-based comparisons of network lifetimes

For the evaluation of the various network lifetime definitions surveyed in this paper, as well as our new definition, we used the setup described in [38]. To obtain sample data for the evaluation, we ran a simulation with 160 sensor nodes placed in an area of 400x400 m^2. The nodes used energy only for communication, and the power consumption values were taken from measurements on Mica2 nodes presented in [78]. The nodes only had a very small, randomly distributed supply of energy at their disposal. The nodes followed random sleep cycles and communicated regularly with a base station in the middle of the

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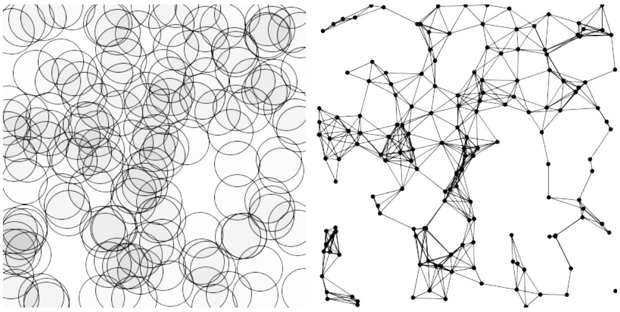

Fig. 1. Coverage and connectivity for the sample setup at time $t = 0$

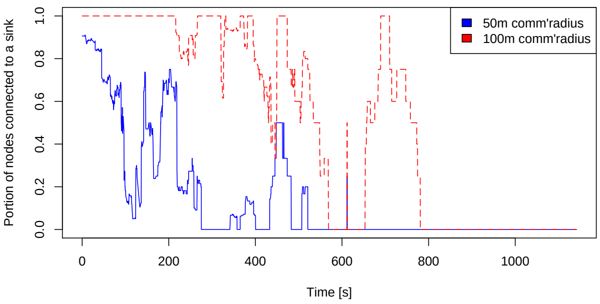

Fig. 2. Evolution of the connectivity criterion over time

simulation area during their awake periods. A number of sensor types was randomly selected from the three types available for each node.

Figure 1 shows the distribution of the nodes in the sample setup at time $t = 0$, as well as the initial coverage with a sensing radius of 30m and the communication graph for a communication range of 50m.

During the simulation, we recorded the positions of the nodes, their failure times, their sleep periods, and the types of sensors available on each node. We conducted only a single run of the simulation, as the purpose was not to obtain statistically significant simulation output, but to obtain sample values for the evaluation of the network lifetime definitions.

Figure 2 illustrates the interaction of sleep cycles and node failures in the sample setup on the basis of the connectivity metric. The portion of nodes with a path to a sink node was computed for communication radii of 50m and 100m.

In order to demonstrate the impact of the various parameters, we evaluated the network lifetime varying one parameter at a time while switching the other parameters off. There were two exceptions to this: the parameter c_k was varied together with the coverage parameters, and c_{sd} was varied with all other parameters. The communication range was fixed as a circle with 50m radius, while the sensing range was a circle with a radius of 30m.

All criteria involving target coverage were evaluated with four different target placements: one scenario with only three targets in the middle and in two corners of the area, and three scenarios with ten randomly placed targets each.

In total, we computed the network lifetime for more than 3000 different parameter settings. The best case lifetime (i.e. the time of the last node failure) reachable in the sample setup was about 1150 seconds. For the figures below, the lifetime has been normalized to the interval $[0, 1]$.

C. Evaluation of existing definitions

Figure 3 shows an evaluation of the existing definitions of network lifetime in the context of our sample setup. For each definition with a direct mapping to our definition as shown in table IV, we computed the network lifetime with varying parameters. Figure 3 shows a box plot for each definition, indicating the median, the first and third quartile, and the minima and maxima of the achieved total network lifetimes. The same representation is used for all following figures as well.

In the context of the sample network, the definitions can result in very different network lifetimes varying roughly between 0 and 70% of the best case lifetime. In addition, there is a high variance of the resulting lifetime depending on the actual values of the parameter setting used for each definition. This illustrates how difficult it is to compare network lifetimes obtained with different, and possibly custom, lifetime definitions.

D. Impact of service disruption tolerance

To evaluate the impact of the service disruption tolerance parameter we introduced into the definition, we first analyze how the total lifetime Z_t and the accumulated lifetime Z_a behave depending on the length of the service disruption tolerance. Figure 4 shows the resulting lifetimes for all evaluated parameter settings, split by tolerances of 0, 25, 50 and 100 seconds.

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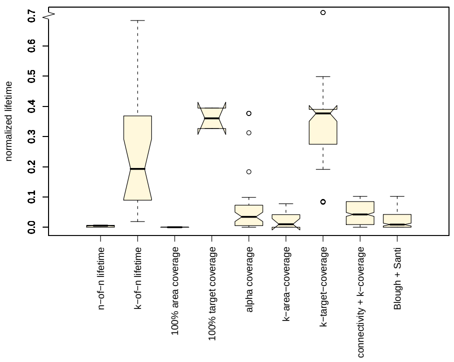

Fig. 3. Evaluation of existing network lifetime definitions

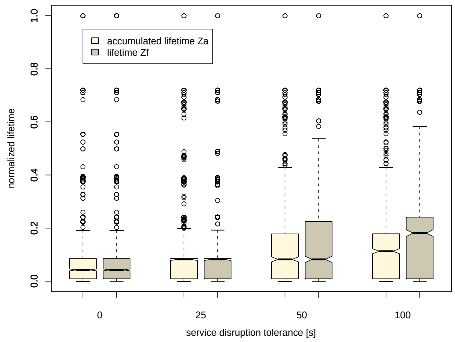

Fig. 4. Overall impact of service disruption tolerance

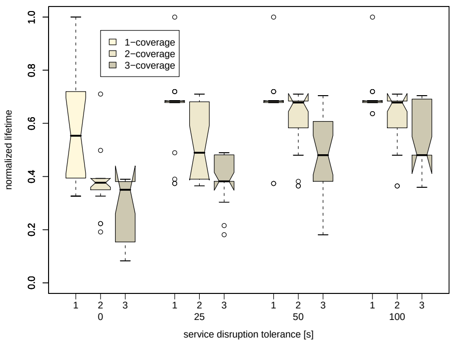

Fig. 5. Target coverage depending on service disruption tolerance and k-coverage

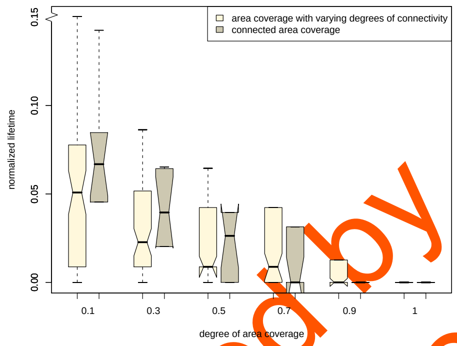

Fig. 6. Connectivity and area coverage vs. connected area coverage

Both lifetime metrics increase with increasing service disruption tolerance. Following from the definition of the metrics, Z_t is only equal to Z_a if the service disruption parameter had no effect, either because it was zero, or because the first service disruption period was already longer than the parameter allowed. In all other cases, Z_t is greater than Z_a.

The figure also demonstrates that the classic lifetime metrics without service disruption tolerance can yield lifetimes that are significantly too low if the network application allows for some amount of service disruption.

In about 65% of the evaluated cases with nonzero lifetime and service disruption tolerance, tolerating some amount of service disruption led to a higher value of the lifetime metrics.

The difference between the accumulated lifetime Z_a and the total lifetime Z_t indicates how long the network was not lively during the lifetime indicated by Z_t and therefore shows the magnitude of the non-lively periods that were tolerated. As could be expected, with increasing service disruption tolerance increasingly large non-lively periods are tolerated. However, the exact amount of this increase depends strongly on the particular setup of a sensor network and should not be generalized from this figure.

Figure 5 shows how service disruption tolerance and k-coverage influence the lifetime achievable if target coverage is the only criterion. The exact amount of target coverage required is varied between 0 and 1 inside each of the box plots. If the targets are required to be covered by more than one sensor, the lifetime of the network decreases significantly, in some cases by more than 20% of the maximum achievable lifetime. On the other hand, allowing for some amount of service disruption can increase the network lifetime by approximately the same amount. As an example, compare the lifetime for 2-covered targets without service disruption tolerance with the lifetime for 3-covered targets with 25 seconds of service disruption tolerance. The medians of both lifetimes are nearly equal, demonstrating that a tolerance towards service disruptions can compensate higher requirements in other parts of the system to some extent.

E. Evaluation of connected coverage criteria

Another new aspect in our definition of network lifetime is the introduction of the connected coverage criteria. While we assume that this metric is a stronger constraint than connectivity and coverage on their own, the evaluation must provide hints if this is really the case. To ensure that the evaluation is not influenced by other parameters, only parameters related to connectivity and coverage were varied in this section.

Figure 6 shows the network lifetime depending on varying degrees of area coverage. The light boxes represent all cases where there were requirements on the connectivity next to the coverage requirement, whereas the dark boxes represent the

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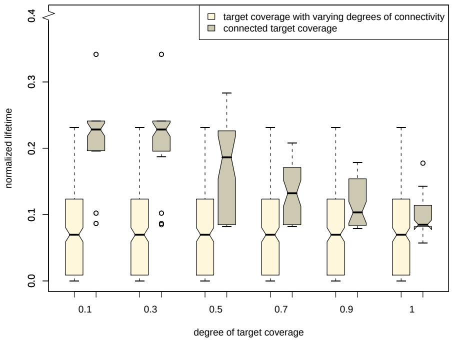

Fig. 7. Connectivity and target coverage vs. connected target coverage

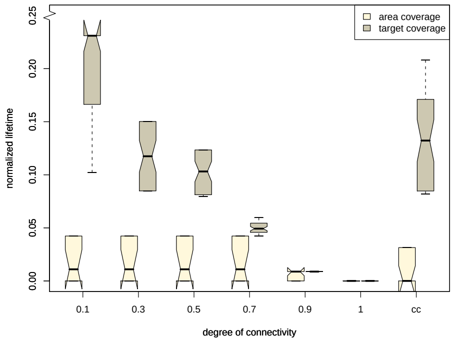

Fig. 8. Connectivity and coverage vs. connected coverage at coverage = 0.7

cases with the connected area coverage requirement. The connectivity required for the light boxes was varied between 0 and 1 for each box. Figure 7 shows the same plot for target coverage instead of area coverage. Figure 8 shows the network lifetime depending on connectivity with the coverage requirements for area coverage (light boxes) and target coverage (dark boxes) fixed at 0.7. The two rightmost boxes show the lifetime achieved with connected coverage fixed at 0.7.

The combination of target coverage and connectivity does not depend on the required level of target coverage, as figure 7 illustrates. This means that connectivity is always a stronger requirement than target coverage. For area coverage, figure 8 demonstrates that the combination of area coverage and connectivity does only depend on connectivity for very large values of area coverage. Therefore, area coverage is in most cases a stronger requirement than connectivity. These observations are probably only valid for the sample setup and not in general. However, they lead to the assumption that in many networks, one of the criteria is a stronger requirement than the other, so that the lifetime only depends on either coverage or connectivity. The connected coverage criteria do not show these dependencies. Therefore, they produce more accurate estimates of network lifetime.

As seen in figures 6-8, the lifetimes calculated with the connected coverage criteria are different from the lifetimes with the two single criteria connectivity and coverage. However, there is no evidence that connected coverage generally results in higher or lower lifetimes.

Connected coverage will result in a higher lifetime if the connectivity percentage requirement is not fulfilled, but there are a few nodes with a connection to a base station providing the required coverage. Connected coverage will result in a lower lifetime if the set of nodes providing connectivity is at least partially different from the set of nodes providing coverage, so that not all of the covering nodes can find a path to a base station.

VII. Conclusion

Motivated by the emergence of network lifetime as the key characteristic of sensor networks that covers typical properties of these networks such as node availability, sensor coverage, and connectivity as well as more sophisticated quality of service properties, several papers have been written that propose algorithms to increase the network lifetime in specific scenarios. We surveyed lifetime definitions in the literature, outlined advantages and drawbacks, and summarized additional requirements. This way, we emphasized the need for a more general and concise definition for accumulated and total network lifetime, that is formal and applicable in various domains. Our definition can be used for analytical evaluation as well as for simulation models to evaluate specific algorithms in a comparable way. Thus, the definition results in more precise estimates of network lifetime, and can represent application requirements for very different sensor network settings. We demonstrated the applicability based on a comparison with the related work as well as using a simple example scenario.

Currently, the definition allows to recognize a network either as lively or non-functional and the lifetime is calculated accordingly. If the need for graceful degradation in the context of fault tolerant systems arises [79], [80], the lifetime definition can be enhanced to support this as well by modifying the single verification parameters to reflect ranges instead of hard limits [81].

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